Universidade do Porto

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# Analysis of atmospheric conditions: data quality and stationarity in Perdigão

José Miguel Almeida Vilaça

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Supervisor: José Manuel Laginha Mestre da Palma

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**Contact information:**
José Miguel Almeida Vilaça
email: em11133@fe.up.pt

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# Abstract

This dissertation concerns the analysis of data of the Perdigão-2017 field experiment (Vale do Cobrão, Portugal). Wind speed, wind direction and temperature measured by sonic anemometers at the top of four towers (three 100 and one 60 m height) and by three remote sensors (radars and sodars and RASS) were analysed to know the atmospheric conditions during the intensive observation period (IOP), from the 1st of May to the 15th of June 2017.

Time series, wind roses, wind profiles and other figures and tables were made with MATLAB software, in order to better organize and visualize the data gathered. Defects in the data, such as missing values and spikes, were detected and corrected in an effort to facilitate the usage of the data sets for this and future works. Furthermore, a search for stationary periods was performed, first with visual analysis, then with the help of more analytical search criteria. Such periods are important, because they provide real life situations which can be compared against computer models. Finally, the stability of the atmosphere was characterized.

It was found that the average wind speed and main direction were in agreement with previous studies. Visual observation showed a relation between wind direction and wind speed, although its exact details were not discovered. Stationary periods were found and characterized based on their average wind speed, direction and temperature. The atmosphere was found to be stable in the areas and heights covered by the remote sensors and unstable in the areas and heights covered by the towers.

# Resumo

Esta dissertação prende-se com a análise de dados da experiência de campo Perdigão-2017, (Vale do Cobrão Portugal). Foram analisadas a velocidade e direcção do vento e a temperatura, medidos por anemómetros sónicos no topo de quatro torres (três de 100 m e uma de 60 m) e por três sensores de medição remota (radars, sodars e RASS),por forma a conhecer as condições atmosféricas durante o período de observação intensiva (IOP), de 1 de Maio a 15 de Junho de 2017.

Foram feitas séries temporais, rosas dos ventos, perfis de vento, entre outras figuras e tabelas, com software MATLAB, para organizar e visualizar melhor os dados recolhidos. Foram detectados e corrigidos defeitos nos dados, tais como valores em falta e picos, na tentativa de facilitar o uso dos conjuntos de dados neste e em trabalhos futuros. Para além disso, foi efectuada uma busca por períodos estacionários, primeiro com análise visual, depois com a ajuda de critérios mais analíticos. Tais períodos são importantes, pois providenciam situações de vida real que podem ser comparadas com os resultados de simulações. Por fim foi caracterizada a estabilidade da atmosfera.

Descobriu-se que a velocidade média do vento e a sua direcção principal estão em acordo com estudos prévios. A observação visual mostrou uma relação entre a velocidade do vento e a sua direcção, no entanto as suas especificidades não foram descobertas. Foram encontrados períodos estacionários e caracterizados no que toca à sua velocidade, direcção e temperatura. A atmosfera foi considereda como estável nas áreas e alturas cobertas pelos sensores de medição remota e instável nas áreas e alturas cobertas pelas torres.

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# Nomenclature

### Abbreviations

agl - Above ground level

asl - Above sea level

ISS - Integrated Sounding System

IOP - Intensive Observational Period

Lidar - Light Detection And Ranging light Imaging Detection And Ranging

NaN - Not a Number

NCAR - National Center for Atmospheric Research

NEWA - New European Wind Atlas

NIMA - NCAR Improved Moments Algorithm

RASS - Radio Acoustic Sounding System

Radar - Radio Detection and Ranging

Sodar - Sonic Detection and Ranging

### Variables

$\alpha$ - Wind shear exponent

$\delta\phi$ - Difference between consecutive $\phi$

$\delta\tilde{\phi}$ - Difference between consecutive $\tilde{\phi}$

$c_p$ - Specific heat at constant pressure

$\phi$ - Generic variable (wind speed [$\mathrm{m\,s^{-1}}$], wind direction [°] or air temperature [°C])

$\tilde{\phi}$ - Moving average of $\phi$

$\Gamma$ - Lapse rate

$g$ - Acceleration of gravity

$H$ - Height (above ground level)

$H_{ref}$ - Reference height (above ground level)

$I$ - Record size

$\mathcal{L}$ - Length of region to be travelled by an air particle

$\mathcal{L}_{cd}$ - Length of computational domain

$m$ - Variable to calculate window size

$t$ - Time

$\mathcal{T}$ - Period of time

$T$ - Air temperature

$\theta$ - Potential temperature

$\overline{V_H}$ - Mean wind speed at height $H$

$\overline{V_{ref}}$ - Mean wind speed at the reference height $H_{ref}$

$z$ - Height (above sea or ground level)

# Chapter 1

# Introduction

## 1.1 Perdigão field experiment overview

The Perdigão field experiment was put in place in order to study and acquire data regarding the influence exerted by an upstream hill with flow separation on the wind speed and downhill turbulence. It was also made to find out how the presence of a wind turbine uphill influences the flow separation downhill. Furthermore, the results of the experiment will help the improvement of models of air pollution in valleys, as well as helping the navigation of aircraft through gusty mountainous terrain. Finally, there is some expectation that this field experiment will provide something of a ”gold standard (...) data set for high-fidelity micro scale simulations and forecasting as well as process studies ” (Witze, 2017).

The data collected, when combined with other observations, will be used to refine the existing models, or create new ones entirely. These models will then be put to use in the energy sector in order to improve its practices (Witze, 2017). The experiment ranged from 2016-12-26 to 2017-06-26, with the Intensive Observational Period (IOP), i.e., the period when more sensors were active, lasting from the 1st of May to the 15th of June 2017. This is the time period studied in this thesis. For more information on the Perdigão Field experiment see the following websites:

- Perdigao[1]
- Perdigao Earth Observing Laboratory[2]

Before the Perdigão experiment, engineers and scientists used, as a benchmark, data collected from the Askervein experiment in 1982/3 however, with the technological improvement of wind turbines, computer models and sensors and the general increase of knowledge on the subject, this data started to get outdated and a better and more complete set was required, hence the need for this new field test (Witze, 2017).

[1] https://windsp.fe.up.pt

[2] https://www.eol.ucar.edu/field_projects/perdigao

### 1.1.1 Members and contributors

Perdigão is one of several field experiments of the New European Wind Atlas project (NEWA). This project is an assortment of studies concerned with mapping wind conditions with Perdigão being the largest of such studies, (Witze, 2017). Although it is a part of the NEWA, Perdigão is an important experiment in its own right, with a great part of the experience being supported by American institutions.

The importance and sheer size of the experiment is reflected not only on the number and quality of the instruments deployed, but also on the number of participants, from the European Union (EU) and the United States (USA) (Witze, 2017).

### 1.1.2 Applications of the data obtained

The amount of data gathered allows for different analysis, from a meteorologist perspective, or a physicist, or, as is the case, an engineer concerned with wind energy applications.

### 1.1.3 Terrain and equipment

The site chosen for the experiment is an approximately 6 km long and 2 km wide section of the Vale de Cobrão valley, the two ridges are 500-550 m at their highest point and it has an irregular terrain coverage with patches of trees and other vegetation (Witze, 2017). It was chosen, in part, due to findings from a previous measurements (e.g. INEGI, 2011; Gomes, 2011; Vasiljevic et al., 2017) revealed that wind patterns of one ridge were affected by turbulence from the other ridge, upwind of the first, (Witze, 2017)and that wind flows almost perpendicular to the two ridges in a NE and WSW direction. These ridges, due to their steepness, generate speed ups in the wind flow, which are of great importance for wind energy applications, since that placing wind turbines along such exposed ridges can increase the resource being harnessed by up to 50% when compared to a valley location. (Mann et al., 2017)

The results of the previous experiments also provided the information required to put the instruments and sensors on the best places, so as to guarantee the best possible measurements of flow variability and topographic effects, (Witze, 2017) furthermore the site already had a wind turbine (D=82 m) installed, which allowed to study turbine wake. Another advantage of the site is that is steeper and higher than Askervein, it therefore has a more complex flow, something which is of greater usefulness to the study of the flow conditions, from a wind energy point of view, but also for meteorologists and physicists concerned with the atmosphere and pollution dispersion. (Mann et al., 2017)

In addition to all of this, there is also the interesting feature that the site has roughly the same size as one grid box for mesoscale models, which facilitates the transition to the microscale further on (Witze, 2017). Being a mountainous terrain also has its advantages, since it allows to study terrain accidents such as ridges, canyons and others, which provide a good insight on how topography affects the wind flow (Fernando et al., 2018). A map of the area covered in the experience can be viewed in Figure 1.1.


Figure 1.1: Sattelite photo of the site, showing the two ridges and the valley between

The effects of terrain are very important in determining the wind patterns, which are also influenced by the overall weather patterns for that place. This means that, in order to have an accurate reading, a great number of instruments in several places are needed. To achieve this, 54 towers with various heights and equipped with several instruments (sonic anemometers, air temperature and humidity sensors, barometers and others) were installed on site, as well as 27 lidars, 2 radars, 2 sodars, 3 RASS, weather balloons and many other instruments.

## 1.2 Objectives

The purpose of this thesis is to study the atmospheric conditions in Perdigão from the 1st of May to the 15th of June 2017, from a global perspective, including wind speed, wind direction and air temperature. This, combined with other works and research, will help further the knowledge of wind and atmospheric behaviour and, hopefully, contribute to improve wind energy technologies and applications.

## 1.3 Outline of the thesis

This dissertation is divided into four chapters. Chapter 1, coming to an end, gives a general view of the work and the field experiment (Perdigão) and the purpose of the present study. The methodology is the topic covered by Chapter 2, whereas the discussion of the results is in Chapter 3. Conclusions and suggestions for future works made up Chapter 4. Appendices contain additional information on MATLAB scripts (Appendix 4.2) , weather types (Appendix .7) and profiles of wind speed, wind direction and temperature measured by remote sensors (Appendix .7).

# Chapter 2

# Methodology

This chapter (sections 2.1 to 2.4) is concerned with the techniques and procedures used for data processing and analysis of the Perdigão experimental data. Section 2.1 identifies the key locations, selected as a reference to characterise the atmospheric conditions during the experiment, whereas section 2.2 describes the measuring equipment. Section 2.3 describes the data, namely its source, content and quality. Atmospheric stability, flow stationarity and the procedure to identify periods of flow stationarity are the objective of section 2.4.

## 2.1 Reference locations

Seven key locations (Figure 2.1 and Table 2.1) were selected as being the most relevant and sufficient to provide an overall view of the atmospheric conditions of the site throughout the IOP.

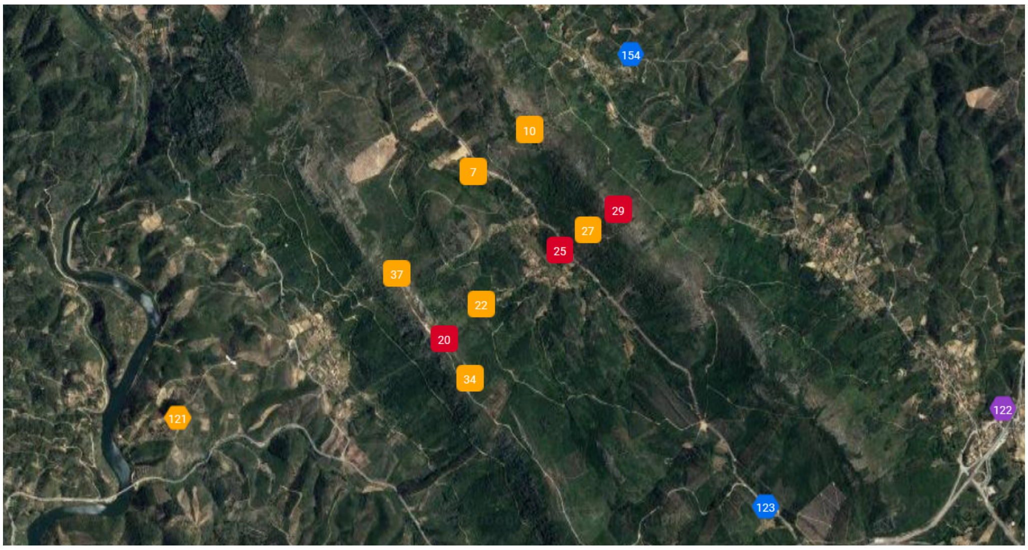



Figure 2.1: Reference points location

Locations 1 to 4 are meteorological towers: the three 100 m towers (20/tse04, 25/tse09 and 29/tse13) located along the WSW-NE transect, and tower 37 (37/rsw06), the climatological tower, near the wind turbine. Locations 5, 6 and 7 (Stations 121, 122 and 123) are remote sensing equipment located southwest of Perdigão (Station 121), in the valley (Station 123) and east of Perdigão (Station 122).

| # | N./Code | Easting | Northing | Elevation |
|---|---|---|---|---|
| 1 | 20/tse04 | 33 394.18 | 4258.87 | 473.0 |
| 2 | 25/tse09 | 34 153.02 | 4844.78 | 305.3 |
| 3 | 29/tse13 | 34 535.99 | 5111.58 | 452.8 |
| 4 | 37/rsw06 | 33 087.97 | 4686.07 | 482.4 |
| 5 | 121/Radar wind profileer RASS (NCAR) | 31654.24 | 3743.27 | 223.7 |
| 6 | 123/Sodar-RASS (NCAR) | 35506.98 | 3177.27 | 361.9 |
| 7 | 122/Radar wind profiler (NCAR/NCAS) | 37056.75 | 3827.09 | 288.6 |

(1) https://windsp.fe.up.pt/experiments/3/station/20

(2) https://windsp.fe.up.pt/experiments/3/station/25

(3) https://windsp.fe.up.pt/experiments/3/station/29

(4) https://windsp.fe.up.pt/experiments/3/station/37

(5) https://windsp.fe.up.pt/experiments/3/station/114

(6) https://windsp.fe.up.pt/experiments/3/station/119

(7) https://windsp.fe.up.pt/experiments/3/station/118

Table 2.1: Reference points location

## 2.2 Measuring equipment

The following instruments were used for gathering the data processed in this study:

- Sonic anemometers in all towers (at several heights): Gill Windtowerer Pro [1];
  - Internal sample rate of 32 Hz;
  - Output parameters at 1, 2, 4, 8, 10, 16, 20 and 32 Hz;
  - Wind speed range: 0-65 m s$^{-1}$; Wind speed resolution:0.01 m s$^{-1}$;
  - Wind direction range: 0- 359°; Wind direction resolution:0.1°;
  - Sonic temperature range: -40 to +70 °C; Sonic temperature resolution: 0.01 °C.
- station 121 [2]:
  - LAP3000 Profiler of 1290 MHz by Radian Corp;
  - Wind speed sampling frequency of 30 min;

[1] https://windsp.fe.up.pt

[2] https://www.eol.ucar.edu/field_projects/perdigao

- 2000 Hz RASS add on;
- Mix of POP4 and LapXM software for data collection;
- height of measurement for wind speed and direction: from 217 m to 4964 4964 m;
- height of measurement for temperature: from 45 m to 1185 m.

- station 122 [3]:
  - LAP3000 Profiler of 1290 MHz by Radian Corp;
  - Wind speed sampling frequency of 30 min;
  - Mix of POP4 and LapXM software for data collection;
  - height of measurement for wind speed and direction: from 263 m to 5809 m;
- Station 123 [4]:
  - Metek DSDPA.90-24 SODAR;
  - Typical sampling frequency of 10 min;
  - vertically pointing 915 MHz 20 W CW RASS radar add-on;
  - all variables: from 40 m to 400 m.

The following are the heights agl of the anemometers studied [5] :

- Tower 37
  - 20.36 m $\approx$ 20 m
  - 30.21 m $\approx$ 30 m
  - 40.19 m $\approx$ 40 m
  - 57.15 m $\approx$ 60 m
- Tower 20
  - 60 m
  - 100 m
- Tower 25
  - 60.15 m $\approx$ 60 m

[3] https://www.eol.ucar.edu/field_projects/perdigao
[4] https://www.eol.ucar.edu/field_projects/perdigao
[5] https://windsp.fe.up.pt

  - $80.28\,\mathrm{m} \approx 80\,\mathrm{m}$
  - $97.14\,\mathrm{m} \approx 100\,\mathrm{m}$

- Tower 29
  - $60.15\,\mathrm{m} \approx 60\,\mathrm{m}$
  - $79.97\,\mathrm{m} \approx 80\,\mathrm{m}$
  - $97.04\,\mathrm{m} \approx 100\,\mathrm{m}$

It is difficult to select the location that can be used as reference for the atmospheric conditions within the whole site. There are several locations that can be chosen, in the following order of importance:

1. 60 m climatological tower (37/rsw06);
2. and either of the three 100 m towers:
   - 20/tse04;
   - 25/tse09;
   - 29/tse13 are the natural candidates, but further work should be done.

Since a reference was needed for this study , the climatological tower was chosen for that purpose.

## 2.3 Data

Data from Perdigão have been uploaded and archived in three alternative repositories (Fernando et al., 2018):

- UPORTO (`http://perdigao.fe.up.pt`);
- US (`https://www.eol.ucar.edu/field_projects/Perdigao`); and
- EU (`http://www.neweuropeanwindatlas.eu`).

under the responsibility of research groups in Portugal (University of Porto, Faculty of Engineering), the USA (NCAR, National Center for Atmospheric Research) and Denmark (DTU, Technical University of Denmark).

In the present work, the tower's data were downloaded from `rodeo.dtu.dk`, an alternative to any of the three sites, taking advantage of a previous dissertation (Martins, 2018) and avoiding the difficulties of dealing with the different user interfaces of the previous three data sites, still under construction. The remote sensors' data (Stations 121, 122 and 123) were downloaded from the US archive.

This dissertation began in February 2017 and a new set of data was announced by Steve Oncley in March 2018, due some time in July 2018, too late for the present study. There are, therefore, some aspects of data quality approached in this thesis that may be resolved by the new data.

The meteorological towers' data were comprised of 10 min averages of measurements by sonic anemometers gathered at a frequency of 32 Hz, but available at 20 Hz (see Section 2.2).

The remote sensors' data were organized into three different manners:

- NetCDF files containing approximately 30 min averages for the west wind profiler (station 121);
- NetCDF files containing 1 and 15 min averages for the NCAS RADAR (station 122);
- Text files with 10 min averages for the ISS SODAR (station 123).

All these files had multiple variables, but only the wind speed, direction and temperature were extracted. Station 122 had no data on temperature.

The Perdigão data are now being analysed by all participants in the experiment. The data currently available are mostly raw and have been submitted to very basic tests, if any. It therefore requires post-processing to remove wrong data (errors), due to instruments malfunctioning and other causes typical of any field experiment. The only data pretreated were of the west wind profiler (Station 121, Table 2.1), where the NIMA algorithm (Morse et al., 2002) was used and of the NCAS RADAR's (station 122), where an unspecified method was used. The identification and removal of these errors was a significant part of the present study.

### 2.3.1 Software used

MATLAB was the main software used. It was used for most operations, from reading the data files (a total of 175, extensions `.txt` or `.nc`, text and NetCDF files), convert to matrices, sort the data, create tables and graphics, to analyse and visualize the gathered information, etc.. MATLAB scripts (in Annex 4.2) were made from scratch, apart from the wind roses, where the MATLAB function *WindRose* (Pereira, 2015) was adapted in scripts made for the purpose of this work. Wind speed, wind direction, and air temperature were the variables of interest and three main types of figures (totalling 16052) were used to display their change during the course of the experiment: time series (702), wind roses (702) and vertical profiles (13822), as well as several others.

### 2.3.2 Data availability

#### Tower data availability

Data availability is an important information when selecting days and atmospheric episodes for further analysis.

For the meteorological towers, data availability was determined as a percentage of valid records in a total of 144 ($24 \times 6$ 10 min averages). Figure 2.2 is an example of one of these days, showing the time series of wind speed, wind direction and sonic temperature.

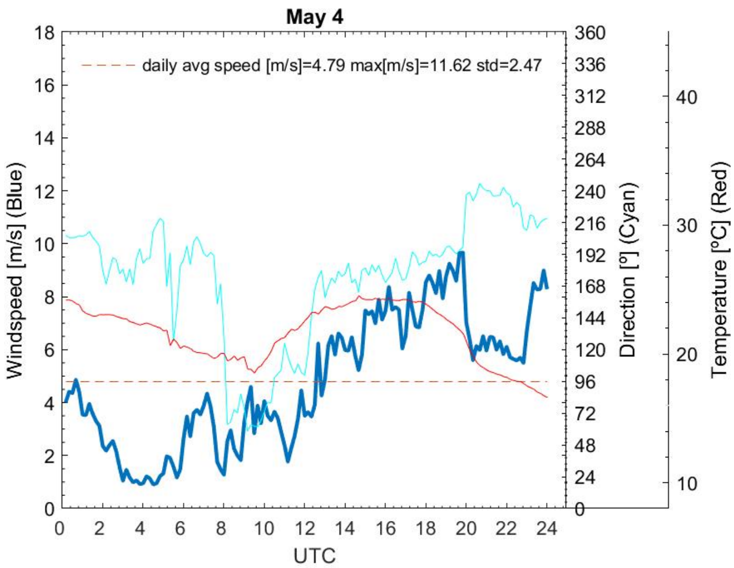



Figure 2.2: 4th of May (tower 20)

The data files contained values of three velocity components, as well as wind direction and temperature. For each of these five variables, values over 10 minutes were given for average, standard deviation, maximum and minimum. The averages and standard deviation were made with data from the files at 20 Hz, the maximum and minimum of the 10 minutes were the corresponding values in 10 minutes of the 20 Hz data.

The files were untreated, therefore had a lot of issues regarding their quality. Poor quality or missing data can occur because of, a wrong measurement, failure to meet criteria set by the data provider, failure of the sensor and/or data logger, among others. The following issues regarding the sonic anemometer's data, were detected (in all variables, except on the last item, which was only detected in wind speed and sonic temperature):

- missing values;
- the number 999.99 appearing in the maximum and minimum values;
- more than two consecutive data points with identical values (freezing of values; not to be confused with the physical freezing of the sensor);

- high values (spikes), above what would be physically accepted.

In order to discover the origin of these errors, the 20 Hz series must be consulted. For instance, the existence of a 999.99 indicates a failure of the sensor/data logger.

In order to filter these errors, new data sets were made from the originals, in which the frozen values were removed. In a second stage, wind speeds greater than $30\,\mathrm{m\,s^{-1}}$ and temperatures greater than 55 °C were also removed via MATLAB. The value of $30\,\mathrm{m\,s^{-1}}$ was chosen because higher wind speeds are of little use to the wind energy industry (see Figure 2.5), whereas the 55 °C were deemed as a temperature to high for that region to be an accurate measurement.

**Remote sensors data availability**

For the remote sensors, data availability was determined as a percentage of valid records of the total of each sensor. The number of records in each sensor was different, since that they record variables at different heights. Two different types of missing records were discovered:

- missing values;
- NaNs.

The data from the sensors was not subjected to any filtering in this study, as no other problems were detected and missing values do not give rise to misinterpretations as, for instance, spikes do.

### 2.3.3 Moving averages

In order to identify stationary periods a script was made to calculate the difference $\delta\phi$ between two adjacent values ($\phi_i$ and $\phi_{i+1}$) in the data series,

$$\delta\phi = \frac{\phi_{i+1} - \phi_i}{\phi_i} \tag{2.1}$$

where, $\phi$ is a generic variable, for instance, wind speed, wind direction or temperature.

An alternative criterion,

$$\delta\tilde{\phi}_i = \frac{\tilde{\phi}_{i+1} - \tilde{\phi}_i}{\tilde{\phi}_i} \tag{2.2}$$

was also used, based on moving averages (Bendat and Piersol, 2000). $\tilde{\phi}$ ,

$$\tilde{\phi}_i = \sum_{i=1}^{I} \sum_{k=i}^{i+m} \frac{\tilde{\phi}_k}{m+1} \tag{2.3}$$

where $I$ is the record size (144, in the case of sonic data with 100% data availability, Section 2.3.2), $m+1$ is the window size, and $m$ is equal to 2, 5 and 11, respectively in the case of a 30, 60 and 120 min time window (see Section 3.5.3).

The figures thus produced provide a visual representation of the variation of the three variables throughout the day, as well as a clearer identification of periods of nearly constant values (see Section 2.4).

## 2.4 Flow stationarity

Atmospheric flows change with time, they are nonstationary, with wind speed and direction depending on the location and time. Atmospheric flows, namely those of interest to wind energy, are always turbulent, vary instantaneously, and are made of a myriad of scales, ranging from a few millimetres (turbulent dissipation scales) to thousands of kilometres (synoptic scales). Separation of turbulent (time) scales in atmospheric flows are accepted to occur around 10 min (cf, Van der Hoven, 1957), i.e. any fluctuation within 10 min is considered as turbulence.

Atmospheric flows are stationary only in statistical terms, i.e. are stationary only in average. Stationary conditions are possible only if the forcing (boundary) conditions prevail for a time ($t$) long enough that within periods of time $\mathcal{T}$ and in a given region of size $\mathcal{L}$ the average values ($\overline{\Phi}$) do not change with time (2.4).

$$\overline{\Phi} = \frac{1}{\mathcal{T}} \int_{-\Delta\mathcal{T}+t}^{t+\Delta\mathcal{T}} \Phi(t)dt \,. \tag{2.4}$$

Many physical models are based on simplified models of atmospheric flows, assuming stationary (equilibrium) conditions. For example, engineering-based models of atmospheric flows used in wind resource assessment and turbine sitting are based on mathematical models with no time dependency at all (Palma et al., 2008). These applications rely on the principle that the flow has a constant speed and direction at all boundaries and no time dependent phenomena are triggered within the computational domain. In order to compare the computational results with experimental data, the identification of stationary periods is required.

In the case of Perdigão, assuming a characteristic length scale of about $\ell = 4500\,\mathrm{m}$ (Figures 2.4 and 2.3, and Table 2.2) and integration domains 10× long $\mathcal{L} = 45\,000\,\mathrm{m}$ (an overestimate one order of magnitude above the real area) or of $\mathcal{L}_{cd} = 19\,000\,\mathrm{m}$ (the actual area used by Silva (2018) in his master thesis), the flow must be stationary during a period of time $\mathcal{T}$; i.e. long enough for a fluid element to travel through the whole length and to every fluid element, passing through the same location, to experience identical conditions. This time period, which will depend both on domain size and wind speed (Table 2.3), will be between 0.08 and 6.25 hours for wind speeds between 16 and 2 m s$^{-1}$.

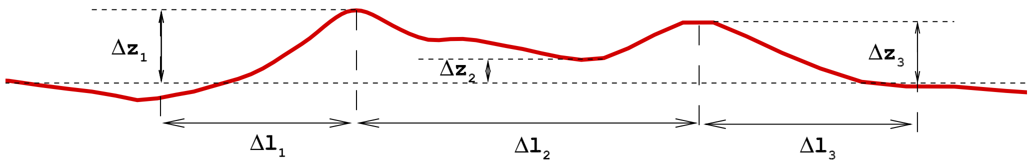



Figure 2.3: Terrain profile at double ridge, (Gomes, 2011). For transect location see Figure 2.4

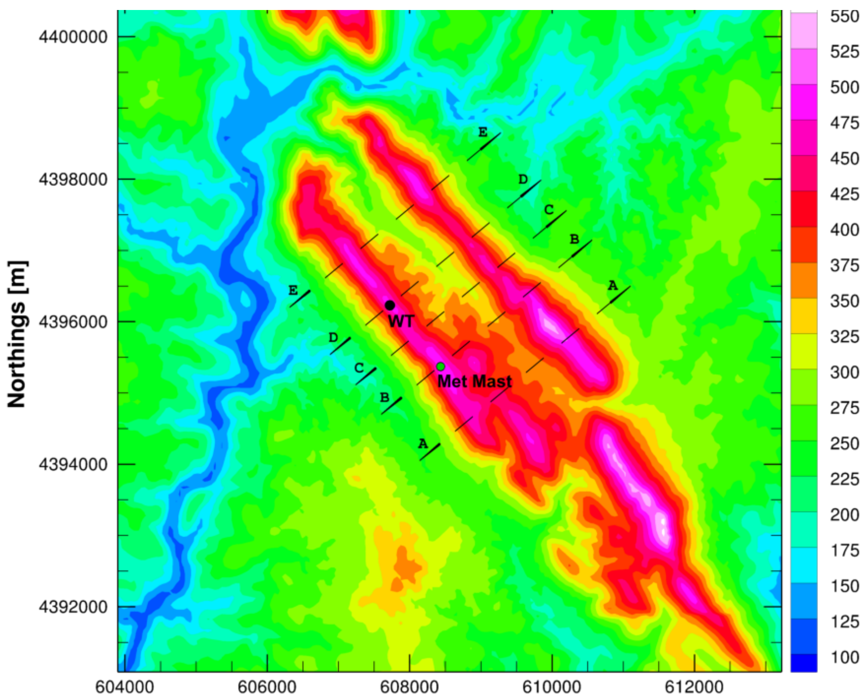



Figure 2.4: Height contour map of double ridge at *Serra do Perdigão*. Met tower (not present at the time of the IOP) and wind turbine locations marked, as well as cross sections used in profiling the double ridge.

| Section | $\Delta z_1$ [m] | $\Delta l_1$ [m] | $\Delta z_1/\Delta l_1$ [%] | [°] | $\Delta z_2$ [m] | $\Delta l_2$ [m] | $\Delta z_3$ [m] | $\Delta l_3$ [m] | $\Delta z_3/\Delta l_3$ [%] | [°] |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 200 | 850 | 23.5 | 12.0 | 100 | 1720 | 255 | 1020 | 25.0 | 14.0 |
| B | 230 | 615 | 37.5 | 18.7 | 80 | 1470 | 205 | 790 | 26.0 | 14.6 |
| C | 215 | 490 | 44.0 | 21.6 | 70 | 1485 | 205 | 610 | 33.5 | 18.5 |
| D | 255 | 720 | 35.5 | 17.7 | 75 | 1385 | 210 | 790 | 26.5 | 14.8 |
| E | 265 | 900 | 29.5 | 14.8 | 75 | 1310 | 230 | 1395 | 16.5 | 9.4 |

Table 2.2: Measurements for terrain profile at double ridge, sections A through E (Gomes, 2011).

| Wind | Hour | | | minute | | | $N_{10}$ | | |
|---|---|---|---|---|---|---|---|---|---|
| speed | $\mathcal{T}_\ell$ | $\mathcal{T}_\mathcal{L}$ | $\mathcal{T}_{\mathcal{L}_{cd}}$ | $\mathcal{T}_\ell$ | $\mathcal{T}_\mathcal{L}$ | $\mathcal{T}_{\mathcal{L}_{cd}}$ | $N_\ell$ | $N_\mathcal{L}$ | $N_{\mathcal{L}_{cd}}$ |
| 2 | 0.63 | 6.25 | 3.13 | 37.50 | 375.00 | 187.50 | 4 | 38 | 19 |
| 3 | 0.42 | 4.17 | 2.08 | 25.00 | 250.00 | 125.00 | 3 | 25 | 13 |
| 4 | 0.31 | 3.13 | 1.56 | 18.75 | 187.50 | 93.75 | 2 | 19 | 9 |
| 5 | 0.25 | 2.50 | 1.25 | 15.00 | 150.00 | 75.00 | 2 | 15 | 8 |
| 6 | 0.21 | 2.08 | 1.04 | 12.50 | 125.00 | 62.50 | 1 | 13 | 6 |
| 7 | 0.18 | 1.79 | 0.89 | 10.71 | 107.14 | 53.57 | 1 | 11 | 5 |
| 8 | 0.16 | 1.56 | 0.78 | 9.38 | 93.75 | 46.88 | 1 | 9 | 5 |
| 9 | 0.14 | 1.39 | 0.69 | 8.33 | 83.33 | 41.67 | 1 | 8 | 4 |
| 10 | 0.13 | 1.25 | 0.63 | 7.50 | 75.00 | 37.50 | 1 | 8 | 4 |
| 11 | 0.11 | 1.14 | 0.57 | 6.82 | 68.18 | 34.09 | 1 | 7 | 3 |
| 12 | 0.10 | 1.04 | 0.52 | 6.25 | 62.50 | 31.25 | 1 | 6 | 3 |
| 13 | 0.10 | 0.96 | 0.48 | 5.77 | 57.69 | 28.85 | 1 | 6 | 3 |
| 14 | 0.09 | 0.89 | 0.45 | 5.36 | 53.57 | 26.79 | 1 | 5 | 3 |
| 15 | 0.08 | 0.83 | 0.42 | 5.00 | 50.00 | 25.00 | 1 | 5 | 3 |
| 16 | 0.08 | 0.78 | 0.39 | 4.69 | 46.88 | 23.44 | 1 | 5 | 2 |

Table 2.3: Stationarity time ($\mathcal{T}$) as a function of wind speed, in the case of length scales $\ell = 4500$ m, $\mathcal{L} = 45\,000$ m and $\mathcal{L}_{cd} = 19\,000$ m

### 2.4.1 Stationary periods?

Wind turbines operate between wind speeds of 3.5 and about 25 m s$^{-1}$ (cut-in and cut-out wind speeds[6]), Figure 2.5. In the case of Perdigão, the mean annual wind speed is about 6 m s$^{-1}$ (Vasiljevic et al., 2017, Table 2) and the time window searched for was between 1 and 2 h, for both length scales ($\mathcal{L}$ and $\mathcal{L}_{cd}$). For a computational domain of size ($\mathcal{L}_{cd}$) equal to 19 km between 2 and 19 consecutive ($N_{\mathcal{L}_{cd}}$) 10 min periods are required to fulfil the stationarity condition, Table 2.3.The maximum (hourly average) wind speed measured during the IOP (Figure 3.17b) was about 16 m s$^{-1}$ (at 60 m in tower 37).

[6] https://www.wind-power-program.com/popups/powercurve.htm

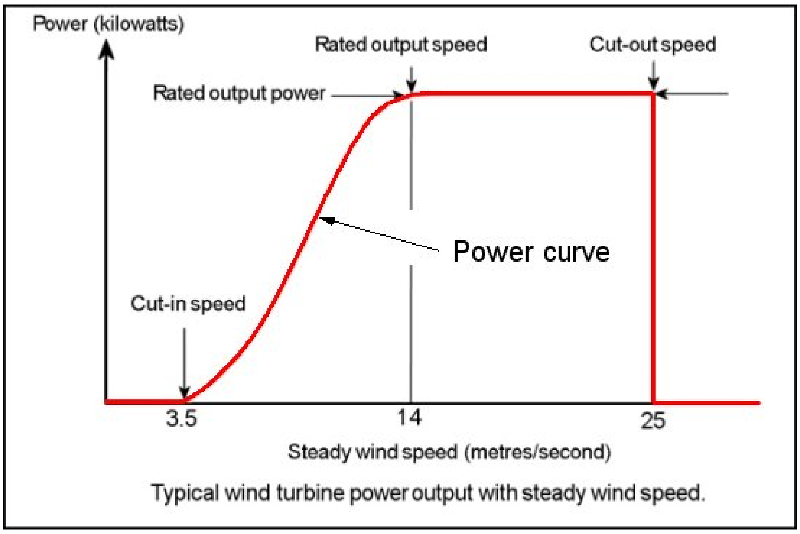



Figure 2.5: Wind turbine power curve

For identification of the stationarity periods these operations were performed in the following order:

1. Visual inspection of time series searching for periods with approximately constant wind speed;

2. On a second approach another set of criteria, concerning wind direction, was adopted. Since that the main flow flows in a northeast–southwest orientation, there was a greater focus on the periods that had directions between $45 \pm 15^{o}$ (northeast) and $225 \pm 15^{o}$ (southwest);

3. Comparing the periods discovered in both observations. It was noted that less evident intervals were discovered on the second approach;

4. After such periods were identified, a number of scripts were created in MATLAB, in order to perform several different operations on the data available (Section 2.3.3), so as to confirm the initial periods encountered, disprove them, or to find new ones that did not show on the initial approach.

## 2.5 Atmospheric stability

In order to determine if the atmosphere is stable, unstable or neutral, the ratio of potential temperature with height was calculated (Kaimal and Finnigan, 1994).

$$\frac{d\theta}{dz} = \left(\frac{dT}{dz} + \frac{g}{c_p}\right) \tag{2.5}$$

The ratio of temperature, $T$, change with height, $z$, is known as lapse rate, $\Gamma$, and defined as (Landberg, 2015):

$$\Gamma = -\frac{dT}{dz} \tag{2.6}$$

where $\theta$ is the potential temperature, $g = 9.81\,\mathrm{m\,s^{-1}}$ the acceleration of gravity and $c_p = 1004\,\mathrm{J\,kg^{-1}\,K^{-1}}$ the specific heat at constant pressure. Depending on $d\theta/dz$ the atmosphere is,

- $$\frac{d\theta}{dz} = 0$$
  neutrally stratified
- $$\frac{d\theta}{dz} > 0$$
  stable
- $$\frac{d\theta}{dz} < 0$$
  unstable

# Chapter 3

# Results and discussion

After presenting the tools and procedures for data analysis (in Chapter 2), a set of results are shown and discussed here. Among those 46 days that comprised the IOP, the results presented here were the ones deemed sufficient to both provide a global view of the IOP and show the effectiveness of the tools developed. The figures containing single days were selected because, for instance, it was a day with wind speeds higher than $6\,\mathrm{m\,s^{-1}}$, with stationary periods, or unreliable data, or because it was a day considered as typical, i.e. one which has conditions very similar to most of the others.

In Sections 3.1 and 3.2 the general atmospheric conditions and data availability are given. Wind roses and time series for all 46 days of the IOP and a selection of a few days are presented in Sections 3.3 and 3.4. Section 3.5 deals with the identification of stationarity conditions. Profiles of wind speed, wind direction and temperature, and atmospheric stability are the topics of the last two sections (3.6 and 3.7) in this chapter.

## 3.1 Overall conditions

Table 3.1 was partially filled (wind speed and temperature), continuing previous work on the subject, and contains the information considered sufficient for a description of every day of the IOP. It could not be either too general nor too detailed. Atmospheric conditions were described based on synoptic (headings, Synoptic regimes and General) and local flow conditions (headings, Local:), of importance respectively for those more interested in atmospheric science and in wind energy.

| Day | Atmospheric conditions | | | | | | | | | | | | | | | | | Flow feature | | | Equipment |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Synoptic regimes | | General | | | | | | Local: 60 m (climatological) tower (37 riSW_06) | | | | | | | | | | | | |
| | | | Clouds | | | | | | Wind speed | | Wind direction | | | | Temperature | | | LLJ or waves | Thund | Wake SW | # |
| | Type | Weather | *Clear sky* | *High* | *Middle* | Low | Thunder storm | Fog | *Average* | *Max* | *Q1* | *Q2* | *Q3* | *Q4* | *Average* | *Max* | *min* | | | | |
| 1-mai | S3 | Clear sky | X | | | | | | 2,97 | 6,828 | | | | | 14,5 | 21,9 | 8,29 | | | | 1 |
| 2-mai | S3 | Clear sky | X | | | | | | 2,50 | 7,805 | | | | | 20,7 | 27,8 | 14,2 | X | | | 1 |
| 3-mai | B1 | High clouds (evening) | | X | | | | | 4,82 | 11,62 | | | | | 24,0 | 30,4 | 16,7 | X | | | 2 |
| 4-mai | B1 | High and low clouds | | X | | X | | | 4,68 | 13,05 | | | | | 22,2 | 26,6 | 17,3 | | | X | 2 |
| 5-mai | B1 | Thunderstorm (afternoon) | | | | | X | | 7,40 | 12,3 | | | | | 16,1 | 18,7 | 12,2 | | | X | 3 |
| 6-mai | B1 | Low clouds (morning) | | | | X | | | 3,24 | 8,788 | | | | | 16,6 | 22 | 12,1 | | | X | 3 |
| 7-mai | B1 | Clear sky | X | | | | | | 5,27 | 13,41 | | | | | 21,4 | 28,4 | 15,6 | X | | | 3 |
| 8-mai | B1 | Middle clouds (afternoon) | | | X | | | | 3,18 | 9,821 | | | | | 24,3 | 30,4 | 18,8 | X | | X | 3 |
| 9-mai | B1 | Low clouds | | | | X | | | 5,83 | 8,901 | | | | | 19,0 | 24,6 | 15,8 | | | | 3 |
| 10-mai | B1 | Thunderstorm (late afternoon) | | | | | X | | 6,45 | 11,81 | | | | | 16,9 | 19,3 | 15,2 | | | X | 3 |
| 11-mai | W1 | Thunderstorm (afternoon) | | | | | X | | 8,67 | 9,88 | | | | | 16,0 | 17,6 | 13,8 | | | | 3 |
| 12-mai | W1 | Low clouds | | | | X | | | 7,01 | 7,786 | | | | | 17,3 | 19,9 | 15,3 | | | | 3 |
| 13-mai | W1/W2 | Low clouds | | | | X | | | 4,80 | 8,913 | | | | | 16,1 | 20,3 | 12,6 | | | | 3 |
| 14-mai | S3 | Low clouds (fog near sunrise) | | | | X | | | 2,68 | 8,113 | | | | | 18,5 | 22,9 | 14,7 | | | | 4 |
| 15-mai | S3 | High clouds | | X | | | | | 4,17 | 9,225 | | | | | 22,7 | 27,9 | 16,7 | X | | | 3 |
| 16-mai | S3 | High clouds | | X | | | | | 4,01 | 9,292 | | | | | 26,2 | 32,4 | 21,2 | X | | | 3 |
| 17-mai | W3/S2 | Middle clouds (until 17UTC) | | | X | | | | 4,27 | 12,01 | | | | | 23,8 | 29,8 | 15,3 | X | | | 4 |
| 18-mai | S2 | Clear sky | X | | | | | | 6,22 | 11,12 | | | | | 15,8 | 21,4 | 12,5 | | | | 4 |
| 19-mai | S2 | Clear sky | X | | | | | | 5,63 | 14,1 | | | | | 17,0 | 24,5 | 10,8 | | | | 3 |
| 20-mai | S2/W3 | High clouds (evening) | | X | | | | | 8,24 | 18,46 | | | | | 22,2 | 28,9 | 14,4 | X | | | 3 |
| 21-mai | S3 | High clouds (low clouds in evening) | | X | | | | | 8,67 | 20,66 | | | | | 24,0 | 29,5 | 20,2 | X | | | 3 |
| 22-mai | S3 | Low clouds | | | | X | | | 3,47 | 8,521 | | | | | 23,2 | 30,1 | 18,1 | | | X | 3 |
| 23-mai | S3 | Clear sky | X | | | | | | 7,10 | 16,53 | | | | | 27,7 | 33,7 | 20,6 | X | | | 3 |
| 24-mai | B2 | Thunderstorm (evening) | | | | | X | | 5,79 | 15,22 | | | | | 25,4 | 35,7 | 20,9 | X | | | 3 |
| 25-mai | S3 | Thunderstorm (until 07UTC) | | | | | X | | 2,16 | 5,832 | | | | | 27,1 | 33,8 | 21,0 | | | | 3 |
| 26-mai | S3 | Thunderstorm (< 02UTC) and fog near sunrise | | | | | X | | 5,65 | 8,787 | | | | | 21,4 | 27,9 | 16,8 | | | X | 3 |
| 27-mai | S3 | Low and high clouds | | X | | X | | | 3,51 | 9,318 | | | | | 22,2 | 27,8 | 16,9 | | | X | 3 |
| 28-mai | S3 | Low and middle clouds | | X | X | | | | 5,01 | 8,351 | | | | | 20,1 | 24,8 | 17,4 | | | | 3 |
| 29-mai | S3/S2 | Low clouds | | | | X | | | 3,24 | 4,915 | | | | | 19,8 | 25,7 | 16,5 | | | | 3 |
| 30-mai | S2/W3 | Clear sky (low clouds in afternoon) | X | | | X | | | 4,00 | 4,818 | | | | | 24,3 | 29 | 19,0 | | | | 3 |
| 31-mai | S3 | Clear sky (low clouds in afternoon) | X | | | X | | | 3,99 | 7,649 | | | | | 25,0 | 31,5 | 20,1 | | | | 3 |
| 1-jun | S3 | Clear sky | X | | | | | | 4,42 | 7,337 | | | | | 26,5 | 33,2 | 21,8 | X | | | 4 |
| 2-jun | S3 | Fog near sunrise (high clouds in evening) | | | | | | | 3,93 | 5,632 | | | | | 24,4 | 31,7 | 19,0 | | | X | 4 |
| 3-jun | W3 | High clouds (evening) | | X | | | | | 3,48 | 5,911 | | | | | 20,6 | 27 | 16,1 | | | | 4 |
| 4-jun | W3 | Clear sky | X | | | | | | 4,36 | 8,541 | | | | | 20,0 | 26,9 | 15,5 | | | | 4 |
| 5-jun | S3/S2 | Clear sky | X | | | | | | 5,61 | 6,495 | | | | | 20,0 | 26,9 | 15,9 | | | | 3 |
| 6-jun | S2 | Low clouds (until noon) | | | | X | | | 3,95 | 7,227 | | | | | 21,8 | 29,9 | 16,7 | | | X | 4 |
| 7-jun | S2/W2 | Clear sky | X | | | | | | 5,10 | 11,73 | | | | | 27,5 | 36,1 | 19,9 | | | | 2 |
| 8-jun | W2 | High clouds (afternoon) | | X | | | | | 4,99 | 12,5 | | | | | 27,3 | 34 | 22,4 | | | | 3 |
| 9-jun | W1/S3 | Clear sky | X | | | | | | 3,58 | 5,01 | | | | | 23,8 | 30,3 | 18,0 | | | | 1 |
| 10-jun | S3 | Clear sky | X | | | | | | 3,75 | 8,05 | | | | | 28,1 | 35,3 | 22,6 | X | | | 3 |
| 11-jun | W3 | Clear sky | X | | | | | | 2,83 | 6,55 | | | | | 29,5 | 36,9 | 24,1 | X | | | 3 |
| 12-jun | W3 | Clear sky | X | | | | | | 4,26 | 9,16 | | | | | 32,0 | 40,1 | 26,7 | X | | | 2 |
| 13-jun | S3 | Clear sky (high clouds < 02UTC, 12-15UTC) | X | | | | | | 4,10 | 13,7 | | | | | 28,7 | 36,4 | 19,6 | | | | 2 |
| 14-jun | S3 | Clear sky | X | | | | | | 4,68 | 9,64 | | | | | 27,6 | 35,6 | 21,2 | | | X | 3 |
| 15-jun | S3/W3 | Short mist near sunrise | | | | | | | 2,90 | 6,85 | | | | | 30,0 | 37,5 | 24,5 | | | | 2 |
| Total Nr of Days; average; maximum and minimum | | | 18 | 10 | 3 | 12 | 6 | 0 | 4,71 | 20,66 | | | | | 22,6 | 40,1 | 8,29 | 15 | 0 | 11 | |

Table 3.1: Perdigão IOP summary catalog

### 3.1.1 Flow conditions

Table 3.1 contains two major parts: the leftmost columns, with the weather and atmospheric conditions (Appendix .7) as well as the occurrence of major flow features; and the rightmost column, on the operating conditions of equipment and data availability. The table can be read along a row for a description of the conditions of a given day, or along a column to find the number of a given occurrence during the whole campaign.

**Synoptic conditions** - the first two columns on the left contain the synoptic conditions, accordingly to eight weather types (Appendix .7)

- *Cloudiness*: clear sky, high, middle and low clouds;
- *Thunderstorm* and *Fog*.

**Local flow conditions** : a summary of the wind conditions during the day, as measured by sensors on climatological tower (37/rsw06). The information here was considered to be most useful for those with wind energy related questions.

- *Wind speed*: average and maximum value;
- *Wind direction*: in terms of quadrants, where a period of at least 2 hours in a quadrant yields a cross (not filled during this thesis);
- *Temperature*: average, maximum and minimum;

**Flow feature** : the occurrence of phenomena of interest.

Four major flow features were found worthy of identification: low level jets, gravitational waves, thunderstorms and wind turbine wake from southwest winds.

**Equipment** : this is a summary of the worksheet; *Equipment*, i.e. the number of instruments operating on the day

Table 3.1 helps to interpret and explain some of the results, such as data flaws and days with very high speeds (relative to the others of the IOP), because many of these occurrences correspond to days with storms and other extreme weather phenomena.

Concerning wind energy motivations, the first variables to be analysed are wind speed and direction. However, for a more detailed description of the atmospheric conditions, one needs additional variables to characterize atmospheric stability. For each of these properties it is also important to select the appropriate statistical parameter to be shown, for example, average, standard deviation or minimum and maximum.

### 3.1.2 Box plots

The box and whiskers plot provides information on the average, median, minimum and maximum value of the distribution of velocity in each day and at each height of measurement. Its main utility is to give a measure of how much dispersion there is in the data (Lem et al., 2013).

Figures 3.1, 3.2, 3.3 and 3.4 have the graphs for towers 37, 20, 25 and 29 respectively. The median is represented by an horizontal straight line in each box, while the average wind speed for each day is a red line connecting the several boxes.

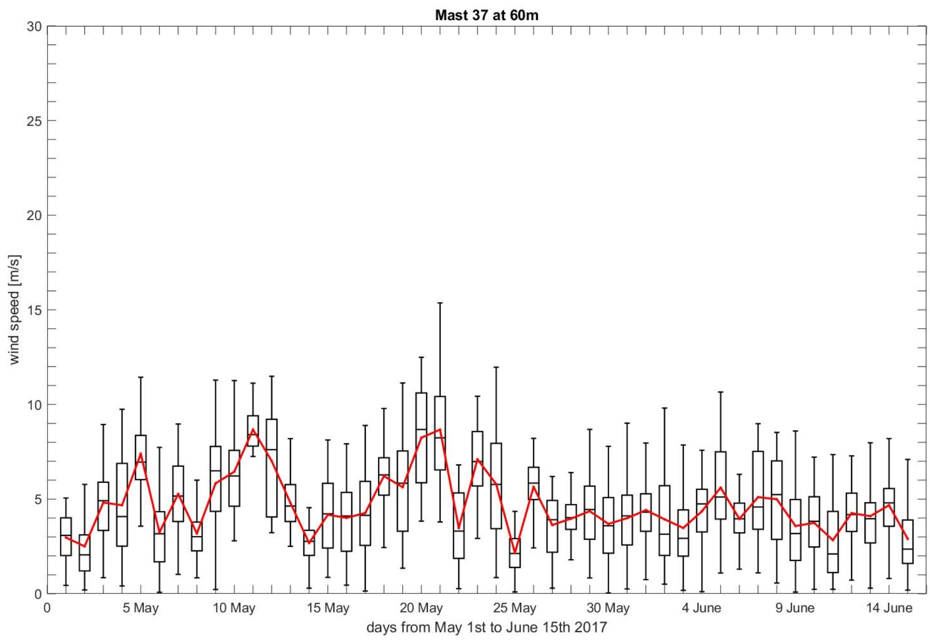



Figure 3.1: Box plot of tower 37 at 60m for all days

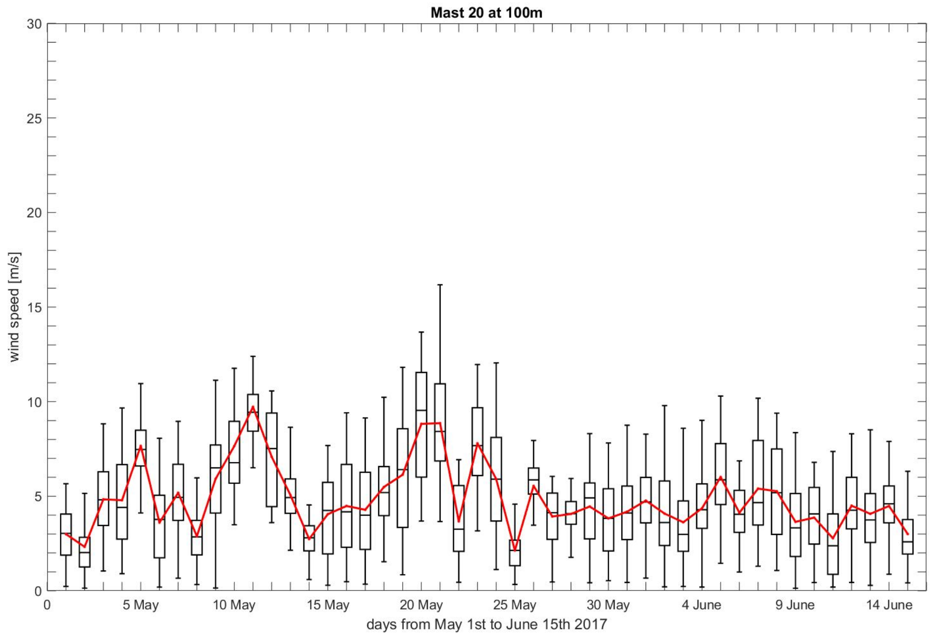



Figure 3.2: Box plot of tower 20 at 100m for all days

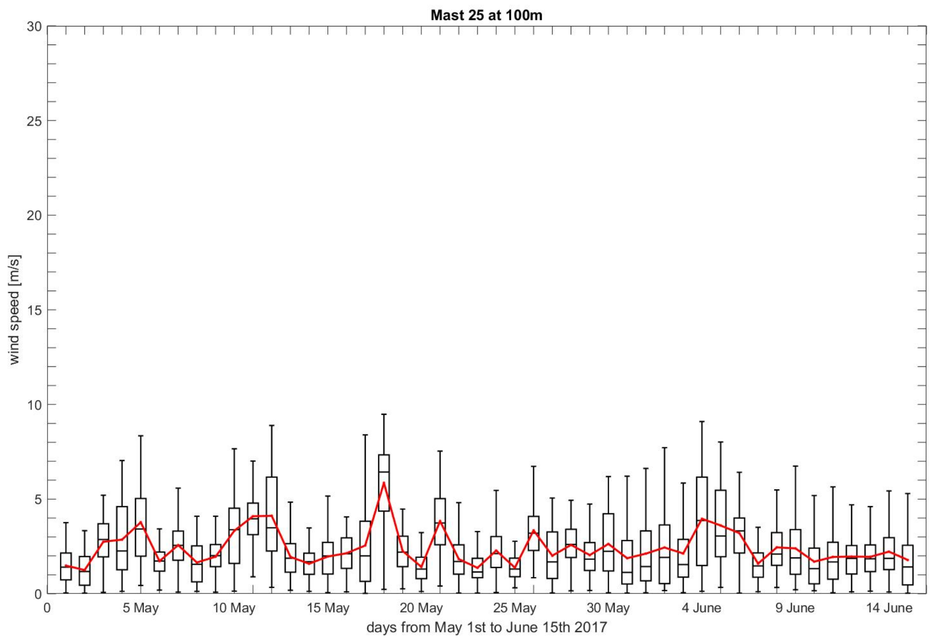



Figure 3.3: Box plot of tower 25 at 100m for all days

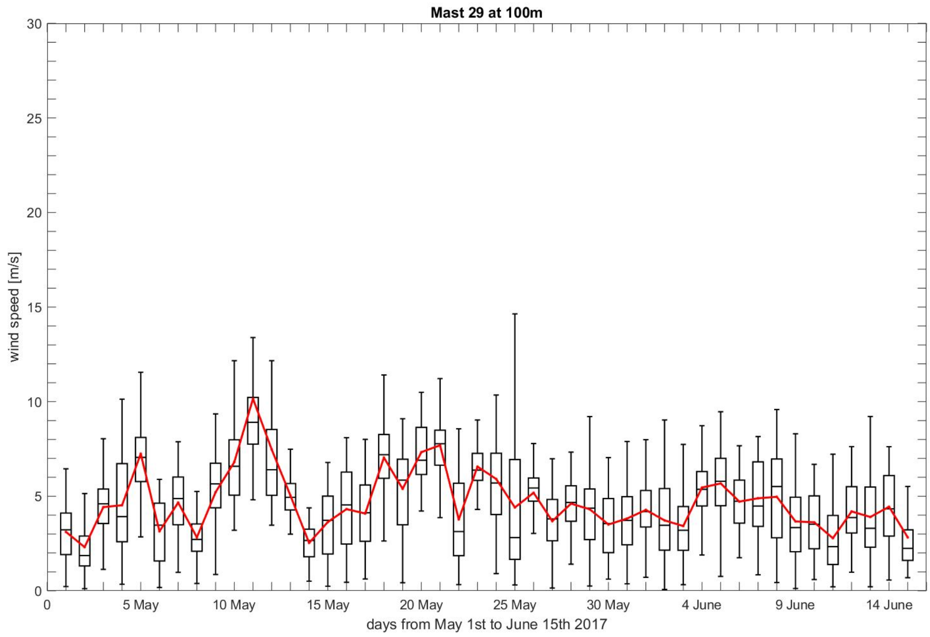



Figure 3.4: Box plot of tower 29 at 100m for all days

Figures 3.1–3.4 show immediately the days with the highest wind speed recorded, and highest average wind speed These days are shown in table 3.2:

| Tower | Maximum speed | Highest average speed |
|---|---|---|
| 37 | May 21 | May 11/21 |
| 20 | May 21 | May 11/21 |
| 25 | May 18 | May 18 |
| 29 | May 25 | May 11 |

Table 3.2: Days with highest speeds

Table 3.2 highest average speed in towers 37 and 20 has the 11th and the 21st, since that, with the measurements available, the 11th has the highest speed, but, as seen in Tables 3.7 and 3.6 that day has very low data reliability. Because of this, it is better to set aside that day and consider the 21st as the one having the highest wind speeds.

Overall the trend on towers 37, 20 and 29 was the same: low speeds at the beginning of the IOP, followed by an increase on the 5th of May, then a decrease, followed by another increase around the 12th of May, then a sharp decrease until the 14th, when it climbed yet again to the high speeds of the 20th and 21st. From then on the speed stabilized around values of 3m/s to 6m/s, with a spike on the 5th of June.

Tower 25, due to its location, suffered a different set of conditions (see Section 3.3 and Figure 3.12) and, as such, the trend is different.

### 3.1.3 Tables of wind speed

#### Tables of average wind speed

Figures 3.3 and 3.4 show the average and maximum wind speed for each day in all towers and sensors. They show the values for 60 m agl and 1000 m. Only these tables are presented, since that the highest anemometer of tower 37 is at 60 m, and it was deemed important to show the values of wind speed at 1000 m (considered as the height at which the ground stops exerting influence on the flow (Landberg, 2015)). Furthermore, there are some days for which there are no measurements whatsoever, as was previously stated. Such days are filled with a "'-"'. All values are in m $s^{-1}$.

It can be seen once again that the 21st of May had the highest recorded wind speed in towers 37 and 20, although not the highest average wind speed. However, if we keep in mind that the 5th and 11th of May had thunderstorms and fewer valid measurements. This can explain the high average wind speeds for those days.

#### Table of wind speed day/night

Table 3.5 shows the result of a visual analysis to the time series at 100 m (60 m for tower 37), with the aim of finding out if certain day had higher speeds at night or during daytime. A high speed was considered to be one above the daily average, for a long period of time (at least 2 hours), a low wind speed was considered to be below the daily average (for at least 2 hours). It can be seen that, for most days, there is no discernible difference between night and day regarding wind speed.

| | 37 | | 20 | | 25 | | 29 | | 123 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Day | Avg | Max | Avg | Max | Avg | Max | Avg | Max | Avg | Max |
| May 1 | 2.97 | 10.24 | 2.91 | 9.05 | 1.18 | 9.15 | 2.93 | 8.41 | 1.31 | 3.43 |
| May 3 | 2.50 | 9.98 | 2.52 | 8.94 | 1.21 | 8.12 | 2.36 | 10.53 | 1.39 | 3.60 |
| May 3 | 4.82 | 11.62 | 4.90 | 11.39 | 1.94 | 10.53 | 4.35 | 11.70 | 1.93 | 4.56 |
| May 4 | 4.68 | 13.05 | 4.58 | 12.46 | 2.33 | 11.49 | 4.49 | 13.98 | 2.31 | 5.39 |
| May 5 | 10.56 | 16.88 | 7.43 | 20.75 | 3.24 | 16.15 | 9.89 | 20.93 | 2.19 | 5.47 |
| May 6 | 3.24 | 8.79 | 3.21 | 9.32 | 1.43 | 8.07 | 2.67 | 8.71 | 1.52 | 3.02 |
| May 7 | 5.27 | 13.41 | 5.18 | 14.40 | 1.88 | 13.59 | 4.45 | 13.76 | 2.59 | 5.38 |
| May 8 | 3.18 | 15.09 | 3.14 | 9.84 | 1.32 | 9.75 | 2.91 | 8.73 | 1.31 | 3.29 |
| May 9 | 5.83 | 17.97 | 5.76 | 17.85 | 1.72 | 12.82 | 4.84 | 16.99 | 2.16 | 6.39 |
| May 10 | 7.40 | 18.53 | 6.69 | 17.66 | 2.91 | 14.93 | 6.22 | 17.70 | 2.29 | 4.94 |
| May 11 | 10.04 | 15.75 | 8.97 | 19.48 | 3.94 | 16.14 | 8.38 | 20.84 | 2.30 | 5.06 |
| May 12 | 7.64 | 16.91 | 7.65 | 17.93 | 3.91 | 18.88 | 8.92 | 22.16 | 3.12 | 6.27 |
| May 13 | 4.80 | 12.95 | 4.76 | 13.18 | 1.63 | 12.37 | 4.69 | 15.40 | 1.90 | 4.11 |
| May 14 | 2.68 | 8.96 | 2.64 | 8.42 | 1.45 | 7.05 | 2.40 | 8.34 | 1.23 | 2.81 |
| May 15 | 4.17 | 9.22 | 4.18 | 9.71 | 1.42 | 7.90 | 3.48 | 8.20 | 1.89 | 5.27 |
| May 16 | 4.01 | 9.29 | 4.09 | 9.64 | 1.42 | 9.35 | 3.87 | 7.49 | 2.23 | 3.99 |
| May 17 | 4.27 | 14.34 | 4.31 | 16.15 | 2.17 | 14.00 | 3.89 | 12.66 | 2.77 | 6.60 |
| May 18 | 6.22 | 17.95 | 5.51 | 16.49 | 5.22 | 18.65 | 6.52 | 17.51 | 4.83 | 8.14 |
| May 19 | 5.63 | 14.10 | 5.58 | 14.76 | 2.01 | 12.27 | 4.80 | 10.81 | 3.12 | 6.76 |
| May 20 | 8.24 | 18.46 | 8.37 | 16.05 | 1.53 | 13.18 | 6.82 | 15.67 | 2.44 | 7.00 |
| May 21 | 8.67 | 20.66 | 8.54 | 21.13 | 2.96 | 12.94 | 7.31 | 14.07 | 3.87 | 7.98 |
| May 22 | 3.47 | 8.52 | 3.40 | 8.85 | 1.27 | 9.68 | 3.53 | 10.72 | 1.88 | 4.37 |
| May 23 | 7.10 | 16.53 | 7.31 | 15.41 | 1.49 | 13.85 | 5.89 | 14.51 | 2.22 | 5.50 |
| May 24 | 5.59 | 15.22 | 5.84 | 17.27 | 1.72 | 20.80 | 5.77 | 21.44 | 3.14 | 5.80 |
| May 25 | 2.90 | 8.55 | 4.28 | 8.72 | 1.43 | 6.06 | 4.15 | 18.40 | 1.87 | 6.73 |
| May 26 | 5.65 | 10.93 | 5.59 | 12.39 | 2.72 | 10.02 | 5.16 | 13.37 | 2.93 | 7.36 |
| May 27 | 3.51 | 10.12 | 3.44 | 9.49 | 1.69 | 10.65 | 3.44 | 11.29 | 1.67 | 4.62 |
| May 28 | 5.01 | 12.13 | 5.00 | 12.67 | 2.61 | 13.21 | 5.11 | 16.29 | 1.97 | 4.31 |
| May 29 | 3.24 | 11.41 | 3.27 | 13.63 | 1.64 | 10.94 | 3.09 | 12.24 | 1.76 | 4.48 |
| May 30 | 3.96 | 12.50 | 4.14 | 12.96 | 2.51 | 10.96 | 3.64 | 11.74 | 1.60 | 5.09 |
| May 31 | 3.99 | 13.80 | 4.07 | 14.17 | 1.63 | 12.40 | 3.56 | 13.15 | 1.64 | 6.49 |
| June 1 | 4.42 | 14.00 | 4.39 | 15.02 | 1.89 | 13.53 | 3.83 | 13.94 | 1.95 | 5.01 |
| June 2 | 3.93 | 14.52 | 3.88 | 14.91 | 2.29 | 14.04 | 3.57 | 14.14 | 1.73 | 5.71 |
| June 3 | 3.48 | 15.11 | 3.48 | 14.96 | 2.10 | 14.28 | 3.12 | 15.15 | 1.71 | 4.68 |
| June 4 | 4.36 | 12.73 | 3.94 | 12.23 | 3.63 | 16.58 | 4.92 | 14.67 | 3.46 | 7.45 |
| June 5 | 5.61 | 16.28 | 5.54 | 15.78 | 3.08 | 15.08 | 5.15 | 16.17 | 2.94 | 6.69 |
| June 6 | 3.95 | 10.64 | 3.70 | 10.17 | 2.74 | 11.68 | 4.30 | 10.90 | 2.77 | 6.25 |
| June 7 | 5.10 | 11.73 | 5.03 | 12.12 | 1.27 | 9.41 | 4.54 | 9.21 | 1.93 | 6.09 |
| June 8 | 4.99 | 13.60 | 4.99 | 13.11 | 2.01 | 13.32 | 4.77 | 14.49 | 2.36 | 5.69 |
| June 9 | 3.58 | 13.61 | 3.66 | 15.15 | 2.46 | 13.31 | 3.60 | 14.64 | 1.76 | 5.40 |
| June 10 | 3.75 | 12.98 | 3.83 | 13.63 | 1.60 | 11.50 | 3.52 | 11.88 | 1.47 | 4.55 |
| June 11 | 2.83 | 12.78 | 2.97 | 12.99 | 1.61 | 13.38 | 2.83 | 13.40 | 1.42 | 5.08 |
| June 12 | 4.26 | 10.73 | 4.19 | 11.63 | 1.44 | 10.28 | 3.80 | 11.44 | 1.68 | 7.62 |
| June 13 | 4.10 | 13.73 | 4.10 | 12.71 | 1.70 | 10.49 | 3.77 | 11.35 | - | - |
| June 14 | 4.68 | 14.84 | 4.50 | 13.86 | 2.04 | 13.82 | 4.20 | 14.13 | 0.93 | 5.09 |
| June 15 | 2.90 | 12.81 | 2.81 | 12.35 | 1.59 | 12.00 | 2.66 | 13.22 | 1.18 | 5.17 |

Table 3.3: Average and maximum wind speeds at 60 m

| | 121 (1025 m) | | 122 (979 m) | |
|---|---|---|---|---|
| Day | Avg | Max | Avg | Max |
| May 1 | 5.84 | 12.30 | 4.77 | 10.41 |
| May 3 | 5.74 | 9.48 | 4.13 | 8.95 |
| May 3 | 6.72 | 10.17 | 6.17 | 9.69 |
| May 4 | 8.62 | 12.33 | 8.11 | 10.88 |
| May 5 | 11.40 | 17.93 | 10.35 | 17.48 |
| May 6 | 6.32 | 14.63 | 5.12 | 9.35 |
| May 7 | 5.43 | 8.48 | 5.07 | 10.19 |
| May 8 | 7.55 | 26.01 | 6.17 | 10.15 |
| May 9 | 8.47 | 12.45 | 6.83 | 11.47 |
| May 10 | 11.05 | 16.96 | 10.32 | 17.81 |
| May 11 | 14.52 | 18.34 | 12.30 | 16.87 |
| May 12 | 11.95 | 19.42 | 10.26 | 20.11 |
| May 13 | 7.45 | 9.39 | 5.73 | 10.77 |
| May 14 | 6.90 | 27.20 | 4.27 | 7.50 |
| May 15 | 4.90 | 17.75 | 3.16 | 8.58 |
| May 16 | 2.89 | 5.65 | 2.48 | 4.99 |
| May 17 | 5.06 | 19.37 | 4.22 | 10.52 |
| May 18 | 9.11 | 18.79 | 8.11 | 18.33 |
| May 19 | 3.31 | 6.88 | 2.90 | 9.68 |
| May 20 | 6.58 | 16.70 | 5.50 | 13.81 |
| May 21 | 9.45 | 14.96 | 8.76 | 15.14 |
| May 22 | 4.23 | 6.86 | 2.81 | 6.95 |
| May 23 | 8.54 | 12.53 | 5.67 | 10.66 |
| May 24 | 6.36 | 9.78 | 6.46 | 12.44 |
| May 25 | 3.77 | 10.93 | 4.13 | 14.55 |
| May 26 | 3.93 | 7.92 | 3.68 | 9.16 |
| May 27 | N/A | N/A | 5.55 | 11.08 |
| May 28 | 6.72 | 12.10 | 6.17 | 11.23 |
| May 29 | 5.20 | 23.56 | 4.36 | 11.22 |
| May 30 | 2.34 | 5.58 | 2.47 | 8.09 |
| May 31 | 4.12 | 6.99 | 3.11 | 6.56 |
| June 1 | 4.13 | 7.98 | 3.06 | 7.35 |
| June 2 | 4.42 | 7.78 | 4.91 | 9.31 |
| June 3 | 3.69 | 7.74 | 3.51 | 8.04 |
| June 4 | 5.61 | 10.87 | 6.66 | 12.13 |
| June 5 | 5.66 | 14.57 | 4.46 | 14.12 |
| June 6 | 4.85 | 11.42 | 5.17 | 12.81 |
| June 7 | 4.57 | 8.85 | 2.62 | 5.78 |
| June 8 | 5.19 | 7.36 | 4.48 | 7.92 |
| June 9 | 3.59 | 6.31 | 4.48 | 7.92 |
| June 10 | 3.79 | 6.36 | 2.81 | 7.27 |
| June 11 | 4.04 | 25.78 | 2.89 | 4.99 |
| June 12 | 4.00 | 8.99 | 3.18 | 6.56 |
| June 13 | 4.28 | 10.92 | 3.97 | 10.15 |
| June 14 | 4.29 | 24.45 | 2.86 | 6.30 |
| June 15 | 2.78 | 6.67 | 2.66 | 7.08 |

Table 3.4: Average and maximum wind speeds at 1000 m

| | Day | | | | Night | | | |
|---|---|---|---|---|---|---|---|---|
| Day | 20 | 25 | 29 | 37 | 20 | 25 | 29 | 37 |
| 01-May | - | x | - | - | - | | - | - |
| 02-May | - | x | - | - | - | | - | - |
| 03-May | | - | - | - | x | - | - | - |
| 04-May | x | x | - | - | | | - | - |
| 05-May | - | - | - | - | - | - | - | - |
| 06-May | - | - | | | x | - | x | x |
| 07-May | - | - | - | | x | - | - | x |
| 08-May | - | x | - | - | - | | - | - |
| 09-May | x | - | - | - | | - | - | - |
| 10-May | - | x | - | - | - | | - | - |
| 11–12-May | - | - | - | - | - | - | - | - |
| 13-May | x | x | - | x | | | - | |
| 14–15-May | - | - | - | - | - | - | - | - |
| 16-May | | - | | | x | - | x | x |
| 17-May | x | x | x | - | | - | | - |
| 18-May | - | x | x | - | - | - | | - |
| 19-May | | - | | | x | - | x | x |
| 20-May | | x | | | x | - | x | x |
| 21-May | - | - | - | - | - | - | - | - |
| 22-May | | | | | x | x | x | x |
| 23-May | | x | - | - | x | - | - | - |
| 24-May | | - | - | - | x | - | - | - |
| 25–26-May | - | - | - | - | - | - | - | - |
| 27-May | - | x | - | - | - | | - | - |
| 28–30-May | - | - | - | - | - | - | - | - |
| 31-May | x | x | x | - | | | | - |
| 01-June | x | x | x | - | | | | - |
| 02-June | x | x | x | x | | | | |
| 03-June | x | x | - | x | | | - | |
| 04-June | - | x | - | - | - | | - | - |
| 05-June | - | - | - | - | - | - | - | - |
| 06-June | - | - | | - | - | - | x | - |
| 07-June | - | - | - | - | - | - | - | - |
| 08-June | - | x | - | - | - | | - | - |
| 09-June | x | x | - | x | | | - | |
| 10-June | - | - | - | - | - | - | - | - |
| 11-June | x | x | x | x | | | | |
| 12–13-June | - | - | - | - | - | - | - | - |
| 14-June | - | x | - | - | - | | - | - |
| 15-June | x | x | | x | | | x | |

Table 3.5: Prevalence of higher wind speeds in day/night per tower. x, day during which there is a distinct prevalence of higher wind speeds in day or night; - , day for which there is no discernible difference, or not enough quality data.

## 3.2 Data flaws and availability

A number of flaws were identified, filtered and removed, before creating the final figures and tables.

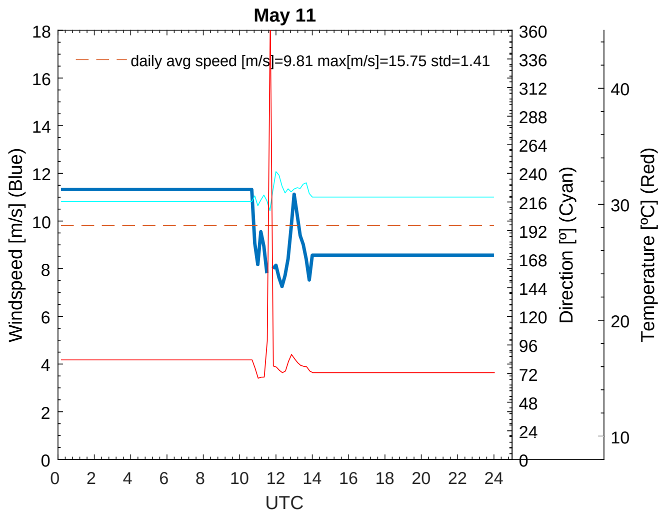



Figure 3.5: Time series of the 11th of May (tower 37 at 60 m agl)

### 3.2.1 Sonic anemometer data flaws and availability

After reviewing the first batch of obtained images a number of problems were identified:

- Days with the same value measured (for example, in the 11th of May on tower 37 at 60 m the temperature was 16.58 °C from midnight to 10:30 am). This, which was observed during the same periods for all other variables, occurred because when the sensor stops measuring, it registers and saves the last value obtained until it starts functioning again (see, for instance, Figure 3.5);
- Spikes (e.g., Mahrt, 1998; Vickers and Mahrt, 1997) of some measurements were also observed, (for instance on the 10th of May, tower 20 at 100 m the temperature jumps from 14.48 °C to 33.11 °C and then to 14.51° in a 30 minute period).
- Error codes (the number 999.99e+02 appearing over and over again in a scattered fashion) (see also Figure 3.5) which indicate that the corresponding 10 min average is contaminated;
- The absence of values for some periods on May 5th and May 30th (since the data

set was for 10 minute averages there should be 144 values for each day, however there were only 114 for the 5th and 80 for the 30th). After closer examination it was noticed that on the 5th there are no values from 03:30 to 08:40 and on the 30th from 00:00 to 10:50. This happened in all towers at the same time.

As an example of the kind of errors discovered, Figure 3.5 shows the time series of the 11th of May, tower 37 at 60m, and it is fairly obvious that it has a lot of wrong values, evidenced by the horizontal straight lines and the huge spike in temperature.

### 3.2.2 Remote sensing data flaws and availability

The quality of the data from stations 121, 122 and 123 was highly heterogeneous, varying from time periods with a full set of measurements, incomplete set or no data.

For instance, temperature had a lower availability compared with the wind speed or the wind direction. For station 122 there is no temperature data, and for station 121, the maximum height of measurement of temperature was smaller than for the wind speed and direction (Figure 3.37).

#### West Wind Profiler (Station 121)

Data from the west wind profiler was 30 minute averaged (29.1 minutes, 30.2, etc) and did not all start at the same time (one set begun the recordings at 00:01:04, other at 00:00:51 etc). It was also discovered that, yet again, the data sets used were plagued with bad data, in this case however, it was found that large portions of the values were filled with `NaNs` and times were missing (for example, on the 13th of May the temperature data sets end at approximately 09:04). On the other hand, since these data sets were quality controlled by NCAR/EOL using the NIMA algorithm the spikes and freezing disappeared which made the task easier. This algorithm may be responsible for the appearance of `NaNs`, together with the fact that the sensors are only able of peak performance under ideal atmospheric conditions[1] (for instance, clean air), and on the field they weren't able to operate at 100% of their ability 100% of the time.

The amount of data rejected translated into several periods, contiguous or not, where not enough data, or none at all, were available, therefore the graphics relating to these periods are not very useful for study. It is also worth noting that no data from the 27th of May exists and no explanation is given for this by the data provider in files used.

#### ISS SODAR RASS (Station 123)

The data of the ISS SODAR RASS was organized in Text files of 10 min averages. The procedures and software for data quality were identical to the West Wind Profiler. There was data missing from some periods, although on the 14th of June whole hours were

[1] https://www.eol.ucar.edu/field_projects/perdigao

missing (no data from 00:00 to 13:50) and there was no data from the 13th. No explanation was provided in the files for the missing day. This data set was not filtered nor subjected to quality control by the data provider.

**NCAS Profiler (Station 122)**

The data from the radar NCAS profiler was available in 1 minute or 15 minute averages, and was given the same treatment, i.e. plotting of 30 minute averages via MATLAB software. Apart from some short periods of missing data, no other errors were encountered. The accompanying `README` file was very clear, identifying:

- the days with electromagnetic interference (30 April; 3, 5–8, 10–12, 16, 20–21 and 25 May), when the winds can be wrong; and
- the missing data periods (30 April, 11:00–14:00; 1 May, 9:00–10:15 and 12:00–15:00; 10 May, 8:30-9:30; 6 June, 20:30–23:59; 7 June, 00:00–16:00.

Figures 3.6–3.8 show examples of time periods without valid measurements for each of the devices. For some time periods no data at all was available, but the figures here contain some data, since it is was both a more recurrent problem and one more relevant to show.

Figures 3.6 and 3.7 show the most common type of bad data: values missing up from a certain altitude. On the eol.ucar.edu website, in the description of the ISS wind profilers, it is mentioned that atmospheric conditions greatly affect the altitude of measurements. The possible explanation for these errors in the data set can, therefore, be attributed to adverse weather conditions.

Figure 3.8 has missing values surrounded by good data. Since this figure comes from the data sets corrected by the NIMA algorithm, the missing values have been rejected by it. Other explanation is that the sensing apparatus malfunctioned in some way. Only by contacting the data provider and accessing the original data sets can this be thoroughly explained .

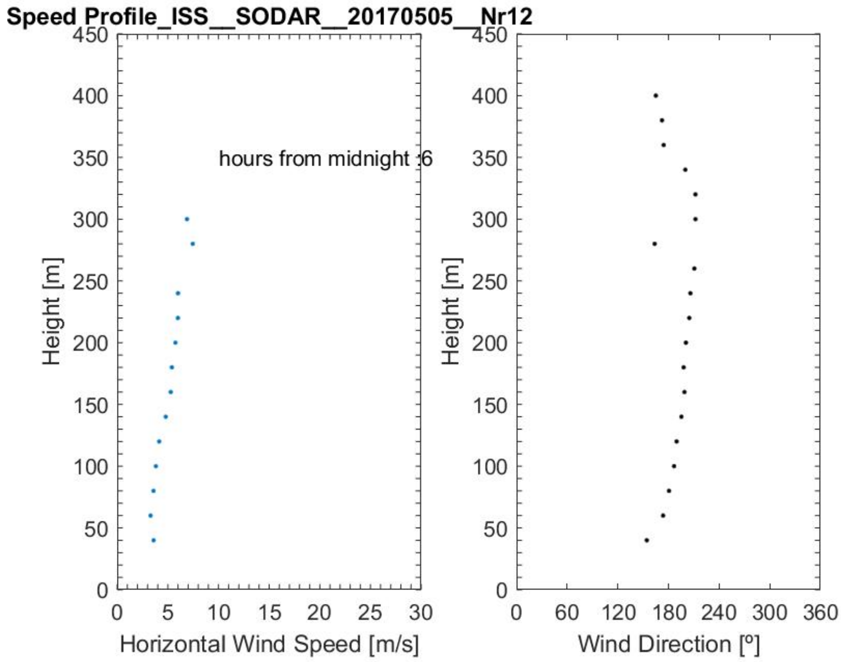



Figure 3.6: Station 123

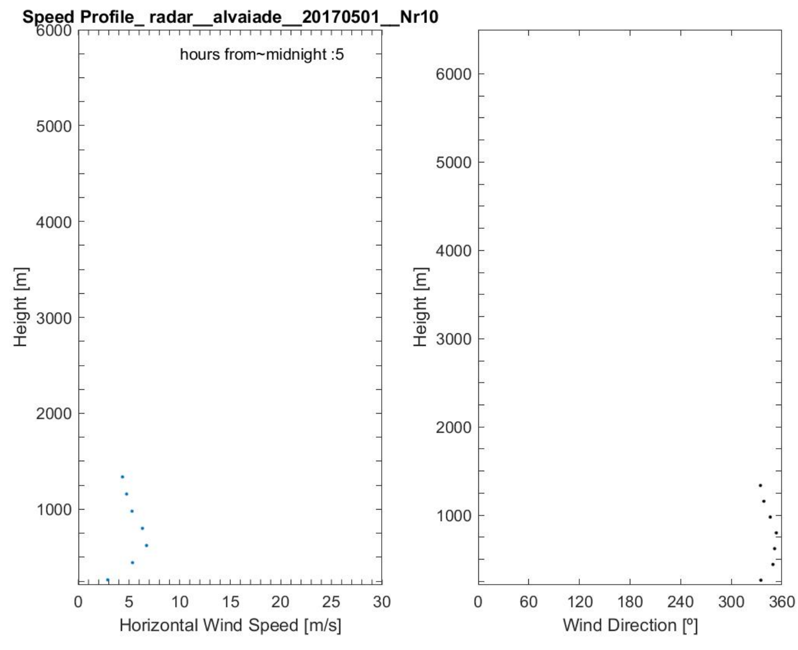



Figure 3.7: Station 122

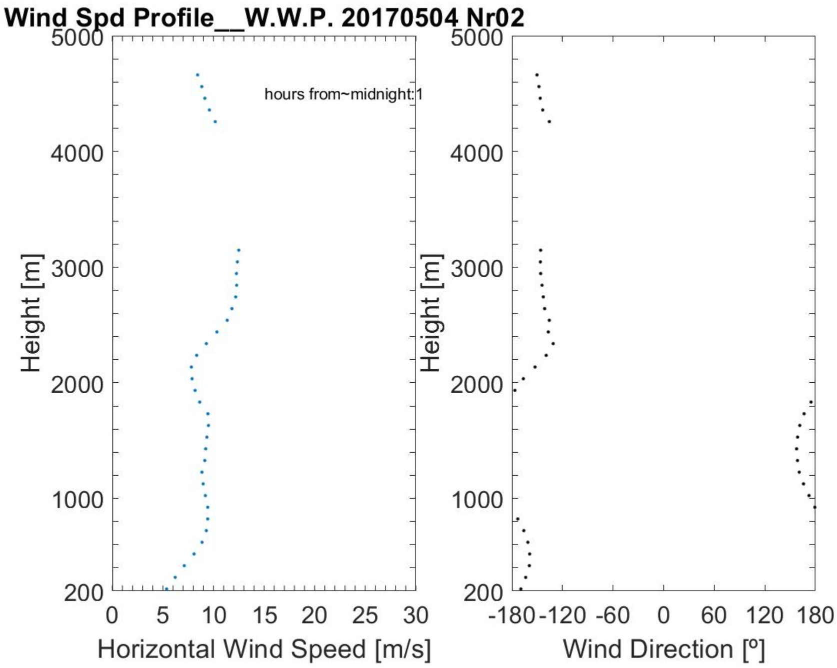



Figure 3.8: Station 121

### 3.2.3 Overall view on data flaws and availability

Tables 3.6 and 3.7 show the availability of data from the sonic anemometers and the remote sensors. The sonic data availability may suffer changes after a new version is made available (Section 2.3.2).

| | Towers | | | |
|---|---|---|---|---|
| Days | 37/rsw06 | 20/tse04 | 25/tse09 | 29/tse13 |
| 01–04 May | 100 | 100 | 100 | 100 |
| 05 May | 77 | 75 | 79 | 76 |
| 06–09 May | 100 | 100 | 100 | 100 |
| 10 May | 81 | 100 | 100 | 99 |
| 11 May | 14 | 58 | 88 | 81 |
| 12May | 56 | 53 | 99 | 78 |
| 13–23 May | 100 | 100 | 100 | 100 |
| 24 May | 89 | 97 | 97 | 100 |
| 25 May | 60 | 63 | 53 | 100 |
| 26–29 May | 100 | 100 | 100 | 100 |
| 30-May | 54 | 54 | 54 | 54 |
| 31 May–15 June | 100 | 100 | 100 | 100 |
| Mean | 94 | 96 | 97 | 98 |

Table 3.6: Data availability [%] (towers 37, 20, 25, 29)

| Day | 121 | 122 | 123 |
|---|---|---|---|
| 01 May | 52 | 27 | 99 |
| 02 May | 41 | 42 | 92 |
| 03 May | 89 | 43 | 95 |
| 04 May | 88 | 57 | 100 |
| 05 May | 71 | 61 | 98 |
| 06 May | 48 | 42 | 97 |
| 07 May | 81 | 48 | 99 |
| 08 May | 85 | 47 | 99 |
| 09 May | 90 | 51 | 100 |
| 10 May | 85 | 64 | 96 |
| 11 May | 84 | 73 | 98 |
| 12 May | 79 | 61 | 98 |
| 13 May | 64 | 53 | 99 |
| 14 May | 59 | 42 | 100 |
| 15 May | 83 | 58 | 92 |
| 16 May | 92 | 66 | 92 |
| 17 May | 84 | 66 | 99 |
| 18 May | 70 | 67 | 96 |
| 19 May | 70 | 33 | 98 |
| 20 May | 82 | 45 | 85 |
| 21 May | 83 | 70 | 83 |
| 22 May | 90 | 52 | 100 |
| 23 May | 84 | 49 | 93 |
| 24 May | 85 | 59 | 98 |
| 25 May | 82 | 71 | 98 |
| 26 May | 82 | 53 | 100 |
| 27 May | - | 47 | 100 |
| 28 May | 82 | 57 | 100 |
| 29 May | 76 | 50 | 100 |
| 30 May | 73 | 47 | 100 |
| 31 May | 85 | 54 | 99 |
| 01 June | 95 | 53 | 99 |
| 02 June | 91 | 52 | 100 |
| 03 June | 83 | 44 | 100 |
| 04 June | 85 | 41 | 98 |
| 05 June | 70 | 43 | 100 |
| 06 June | 78 | 30 | 100 |
| 07 June | 84 | 14 | 98 |
| 08 June | 94 | 52 | 99 |
| 09 June | 78 | 42 | 100 |
| 10 June | 71 | 40 | 100 |
| 11 June | 85 | 46 | 99 |
| 12 June | 95 | 53 | 37 |
| 13 June | 84 | 59 | - |
| 14 June | 80 | 48 | 43 |
| 15 June | 87 | 58 | 82 |
| Mean | 80 | 51 | 93 |

Table 3.7: Data availability [%] (Stations 121, 122 and 123)

The data availability of the four sonics was between 94 and 98% (Table 3.7), and 80, 51 and 93% in the case of remote sensor stations 121, 122 and 123 (Table 3.7). There were a few days, namely 5, 11 and 30 of May, with large portions of data missing. The NCAS profiler had the lowest availability of all.

There are fewer instances of wind speed higher than 30 m s$^{-1}$ on tower 25 than on the others, in fact there is only one such case. In order to find out if it was a measuring or recording error, or if it was a real occurrence, such as a sudden wind gust, the data sets containing measurements of 20Hz for all seconds of an hour need to be consulted. Such an exercise would also be useful on the other towers, in order to have the most correct assessment possible of the data available, and its best interpretation.

Table 3.8 shows the error codes 999.9e+02 on each tower. The values of those days, can be contaminated by such errors and must be analysed in future work.

| | Towers | | | |
|---|---|---|---|---|
| Day | 37/rsw06 | 20/tse04 | 25/tse09 | 29/tse13 |
| 01 May | - | - | - | - |
| 02 May | 2 | - | - | - |
| 03–4 May | - | - | - | - |
| 05-May | 16 | 16 | 9 | 16 |
| 06–7 May | - | - | - | - |
| 08 May | 1 | - | - | - |
| 09 May | - | 1 | 1 | 2 |
| 10 May | 6 | 10 | 3 | 13 |
| 11 May | 3 | 23 | 13 | 61 |
| 12 May | - | - | 10 | 47 |
| 13 May | 2 | 2 | 2 | 2 |
| 14–17 May | - | - | - | - |
| 18 May | 1 | 3 | - | 2 |
| 19 May | 1 | 1 | - | - |
| 20 May | 1 | - | - | - |
| 21 May | 1 | 2 | 2 | - |
| 22–23 May | - | - | - | - |
| 24 May | - | 1 | - | 4 |
| 25 May | - | 1 | - | 6 |
| 26–27 May | - | - | - | - |
| 28 May | - | - | 1 | - |
| 29 May | - | - | - | 1 |
| 30–31 May | - | - | - | - |
| 01–3 June | - | - | - | - |
| 04 June | - | 2 | - | - |
| 05 June | - | 1 | - | - |
| 06–15 June | - | - | - | - |
| Total | 34 | 63 | 41 | 154 |

Table 3.8: Occurrences of 999.9e+02 wind values

## 3.3 Wind roses

Different wind roses were made:

1. with all measurements of all days;
2. after removal of errors (freezing of values);
3. after removal of days without a 24-hour period of availability.

A few wind roses were selected in order to illustrate the results. At first, Section 3.3.2 the wind roses for all days in the 4 towers are presented. Then, in Sections 3.3.3–3.3.5 the wind roses for three days are presented.

### 3.3.1 Wind speed and direction scales

For a good resolution of both the wind speed and direction ranges, 10 wind speed intervals (Table 3.9) and 36 sectors (10 degree angle) were used.

| Wind speed ($m\,s^{-1}$) | Comment |
|---|---|
| $\geq$ 0 and $<$0.28 | calm air according to Beaufort scale |
| $\geq$ 0.28 and $<$ 1 | |
| $\geq$ 1 and $<$ 2 | |
| $\geq$ 2 and $<$ 4 | wind turbine cut-in speed |
| $\geq$ 4 and $<$ 6 | |
| $\geq$ 6 and $<$ 8 | |
| $\geq$ 8 and $<$ 10 | |
| $\geq$ 10 and $<$ 12 | wind turbine nominal wind speed |
| $\geq$ 12 and $<$ 14 | |
| $\geq$ 14 and $<$ 16 | |

Table 3.9: Wind speed range

When setting these scale ranges, other options were considered such as the Beaufort scale, dating back to 1805 and one of the most common scales used, which is made of twelve classes from winds below $1\,km\,h^{-1}$ to above $118\,km\,h^{-1}$; Fernando et al (2015) classified the MATERHORN IOP period based on three classes only, winds below $3\,m\,s^{-1}$ between 3 and $10\,m\,s^{-1}$, and above $10\,m\,s^{-1}$. However, none of these were fine enough and the ranges covered were well above the wind speeds measured during the IOP campaign (Section 3.4).

The colour code range (lower wind speeds in blue and higher wind speeds in red) was chosen to maximize the discrimination between all values and facilitate the reading of the figures.

For wind direction, a 10° sector was chosen, because these 36 bins were fine enough and centred with the main cardinal directions (North, South, West and East), without the loss of definition and general clogging of the figure associated with smaller scales.

### 3.3.2 Wind roses for all days

One of the reasons behind the choice of Perdigão for a large scale field experiment was the assumption that the dominant wind directions would be perpendicular to the ridges, based on a three year (Jan 2002 – Dec 2004) wind resource measurement campaign (e.g. INEGI, 2011; Gomes, 2011; Vasiljevic et al., 2017). Figure 3.9 shows that the majority of wind speeds during the IOP was between 2 and 6 m s$^{-1}$ and confirms the dominant southwesterly or northeasterly winds, i.e. perpendicular to the south or to the north ridge.

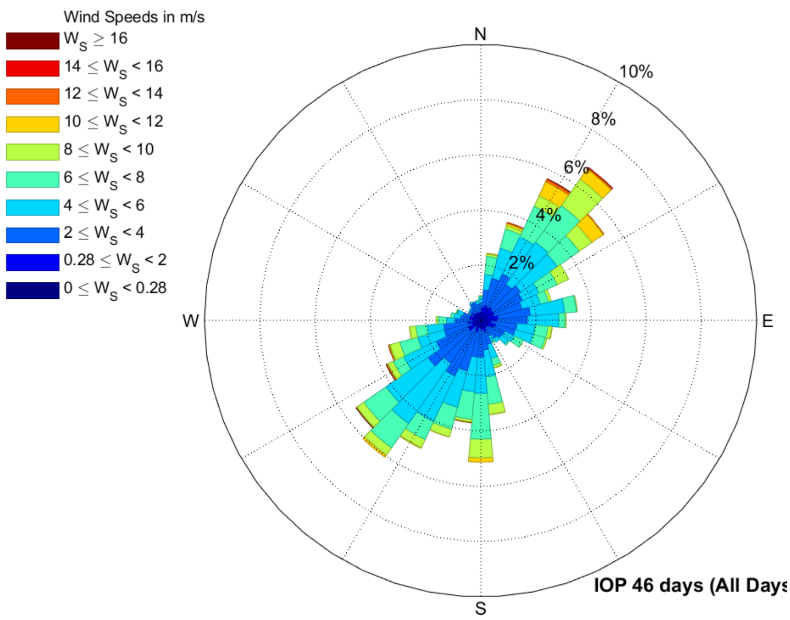
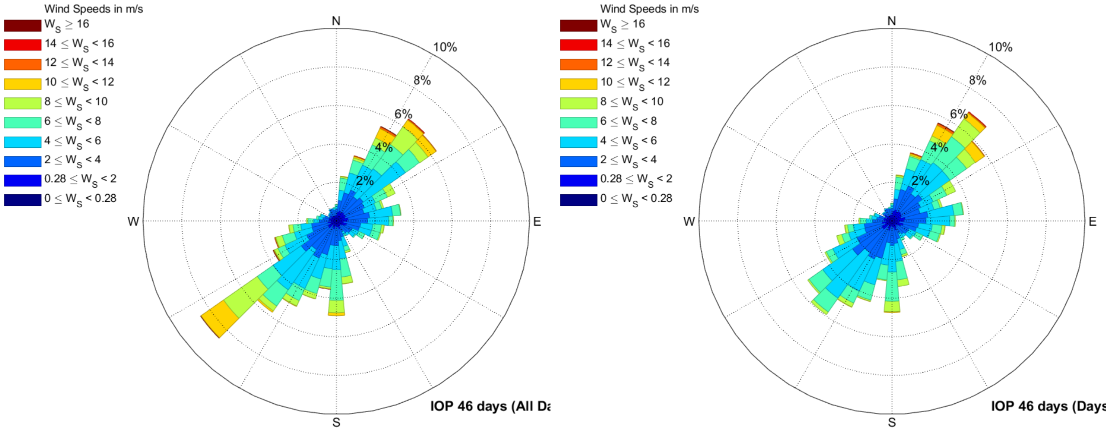



Figure 3.9: Wind rose of the 46 days (tower 37)

Figures 3.10 are also included here as examples of how the wind rose would be with faulty data (3.10a) and removal of those days with faulty data (3.10b). Faulty data here refers only to those periods with constant values ("frozen" data); faulty data criteria are a matter of Section 3.2.




(a) All data (b) Without bad days

Figure 3.10: Wind rose of the 46 days (tower 37), all and bad data

Since that Figure 3.9 is a much more faithful representation of the reality than Figures 3.10, all of the other wind roses presented in this document followed the same procedure, i.e., showing all days while discarding the instances of bad data.

Another useful and important information is the number of occurrences (10 min averaged values) for classes of both wind speed and wind direction, a kind of wind rose in table form, as in Tables[2] 3.10–3.12. Each column represents a 10° range (0° is North and 90° is East) and each line is a wind speed class This gives a quicker view of the amount of time (in groups of 10 minutes, or in percentage of total) a certain wind speed and direction happened. The table is colour coded to facilitate the reading, with the red cells having the most measurements and the green ones the least.

[2]Figures 3.10 –3.12 contain one such table. It was divided into 3 parts because it was too large to fit in the document

| Horizontal Wind Speed Intervals [m/s] | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 | 50-60 | 60-70 | 70-80 | 80-90 | 90-100 | 100-110 | 110-120 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0-0,28 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 |
| 0,28-2 | 37 | 34 | 36 | 31 | 36 | 27 | 36 | 32 | 21 | 20 | 14 | 19 |
| 2-4 | 79 | 68 | 66 | 66 | 79 | 81 | 68 | 58 | 24 | 23 | 17 | 30 |
| 4-6 | 82 | 64 | 35 | 63 | 128 | 96 | 81 | 60 | 17 | 8 | 4 | 3 |
| 6-8 | 6 | 35 | 26 | 39 | 116 | 67 | 69 | 45 | 21 | 1 | 3 | 0 |
| 8-10 | 1 | 4 | 21 | 26 | 55 | 56 | 15 | 6 | 2 | 0 | 0 | 0 |
| 10-12 | 0 | 0 | 0 | 2 | 44 | 44 | 8 | 5 | 0 | 0 | 0 | 0 |
| 12-14 | 0 | 0 | 0 | 0 | 5 | 1 | 6 | 1 | 0 | 0 | 0 | 0 |
| 14-16 | 0 | 0 | 0 | 0 | 0 | 2 | 1 | 0 | 0 | 0 | 0 | 0 |
| >16 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| | total | total | total | total | total | total | total | total | total | total | total | total |
| | 205 | 205 | 185 | 227 | 463 | 376 | 285 | 207 | 85 | 52 | 39 | 52 |
| percentage of total occurences | 3,28 | 3,28 | 2,96 | 3,64 | 7,42 | 6,02 | 4,57 | 3,32 | 1,36 | 0,83 | 0,62 | 0,83 |

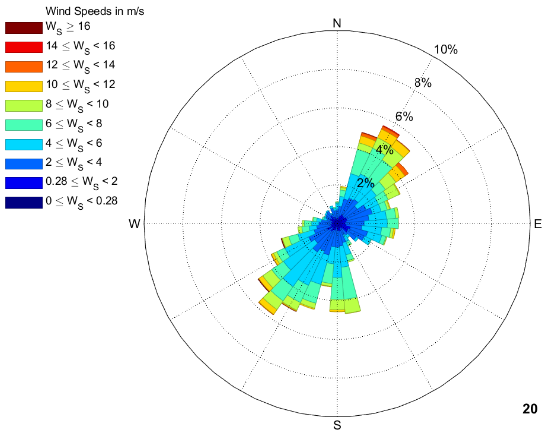
Table 3.10: Bins from 0º to 120º, mast 37 at 60 m.

| Direction Intervals [º] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 120-130 | 130-140 | 140-150 | 150-160 | 160-170 | 170-180 | 180-190 | 190-200 | 200-210 | 210-220 | 220-230 | 230-240 |
| 2 | 1 | 1 | 1 | 0 | 0 | 3 | 0 | 0 | 1 | 1 | 3 |
| 14 | 22 | 18 | 22 | 24 | 19 | 20 | 29 | 23 | 35 | 21 | 20 |
| 12 | 11 | 8 | 16 | 17 | 27 | 48 | 61 | 68 | 105 | 90 | 128 |
| 3 | 5 | 1 | 5 | 19 | 14 | 31 | 47 | 78 | 102 | 134 | 150 |
| 0 | 0 | 0 | 0 | 4 | 11 | 24 | 38 | 34 | 40 | 73 | 51 |
| 0 | 0 | 0 | 0 | 1 | 1 | 7 | 31 | 11 | 13 | 20 | 22 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 4 | 3 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 2 | 0 |
| total | total | total | total | total | total | total | total | total | total | total | total |
| 31 | 39 | 28 | 44 | 65 | 72 | 133 | 210 | 218 | 300 | 345 | 377 |
| 0,50 | 0,62 | 0,45 | 0,71 | 1,04 | 1,15 | 2,13 | 3,36 | 3,49 | 4,81 | 5,53 | 6,04 |

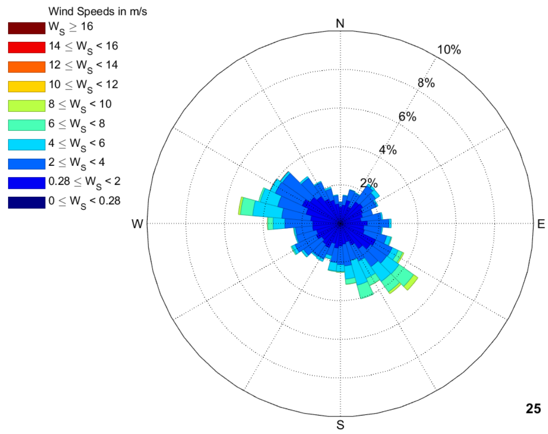
Table 3.11: Bins from 120º to 240º, mast 37 at 60 m.

| 240-250 | 250-260 | 260-270 | 270-280 | 280-290 | 290-300 | 300-310 | 310-320 | 320-330 | 330-340 | 340-350 | 350-360 | total | percentage of total | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 2 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 22 | 0,35 | 0-0,28 |
| 25 | 18 | 24 | 14 | 30 | 19 | 18 | 17 | 27 | 31 | 30 | 28 | 891 | 14,28 | 0,28-2 |
| 101 | 75 | 75 | 50 | 35 | 20 | 23 | 34 | 31 | 38 | 53 | 60 | 1845 | 29,56 | 2-4 |
| 92 | 82 | 83 | 76 | 37 | 27 | 7 | 15 | 20 | 35 | 35 | 55 | 1794 | 28,75 | 4-6 |
| 48 | 48 | 82 | 107 | 21 | 11 | 2 | 1 | 14 | 25 | 37 | 18 | 1117 | 17,90 | 6-8 |
| 19 | 11 | 16 | 46 | 8 | 4 | 0 | 0 | 1 | 1 | 8 | 7 | 413 | 6,62 | 8-10 |
| 2 | 1 | 6 | 4 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 132 | 2,12 | 10-12 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 15 | 0,24 | 12-14 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 0,06 | 14-16 |
| 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 0,13 | >16 |
| total | total | total | total | total | total | total | total | total | total | total | total | | | |
| 288 | 236 | 286 | 297 | 134 | 82 | 51 | 67 | 93 | 131 | 164 | 169 | 6241 | | |
| 4,61 | 3,78 | 4,58 | 4,76 | 2,15 | 1,31 | 0,82 | 1,07 | 1,49 | 2,10 | 2,63 | 2,71 | 100 | 100 | |

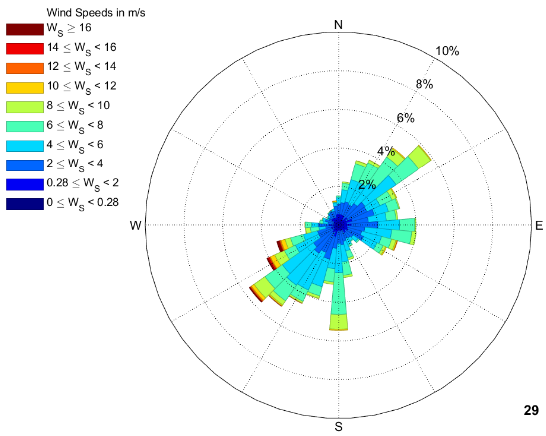
Table 3.12: Bins from 240º to 360º, mast 37 at 60 m.




(a) 20/tse04




(b) 25/tse09




(c) 29/tse13

Figure 3.11: Wind rose of the 46 days (towers 20, 25 and 29).

The comparison between Figure 3.11b (tower 25, in the valley) and Figures 3.9, 3.11a and 3.11c (towers 37 and 25, in the south ridge, and tower 29, in the north ridge) shows that wind direction at the ridges is perpendicular to both ridges, but parallel to the ridges in the valley (Figure 3.11b). The wind speed is also lower in the valley.

Figure 3.12 shows a section of the flow going through the site. In it, it can be seen that the higher wind speeds are on the ridges and that the valley has a recirculation zone, which is characterized by very low speeds. Once the flow passes over the hill, a separation may occur due to different pressure gradients and a recirculation zone forms between separation and reattachment fo the flow (Jiang et al., 2007).

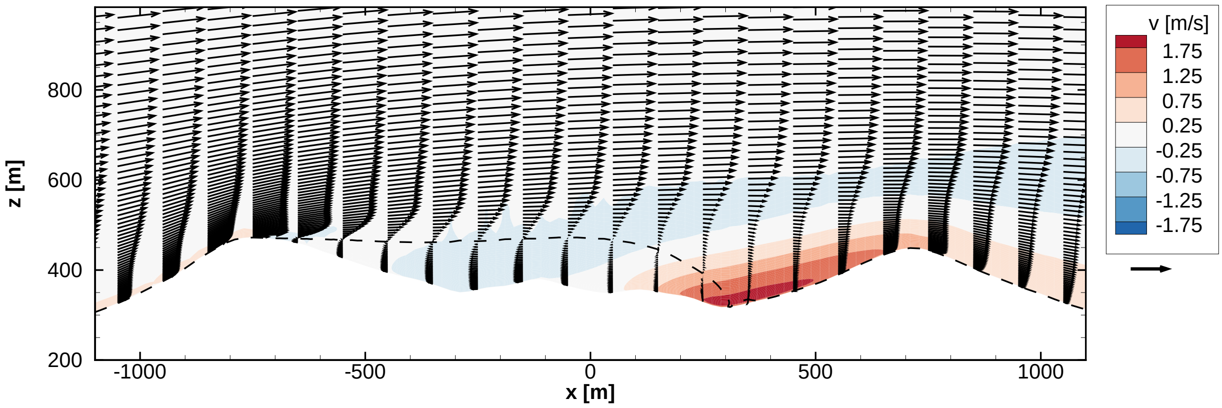


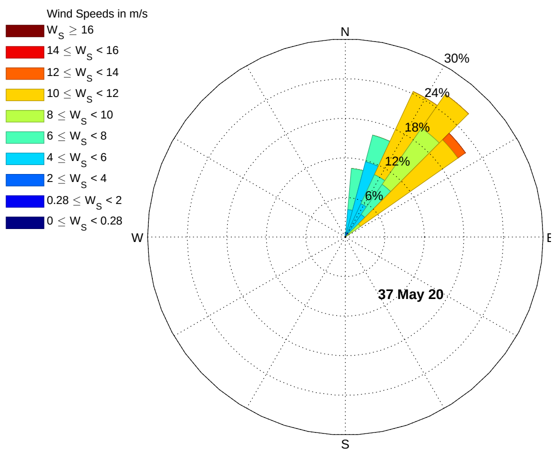

Figure 3.12: Recirculation on the valley, (Silva, 2018).

For a finer view of the conditions during the IOP, the wind roses of three days are also shown next, from towers, 20, 25, 29 and 37 all at the same height, 60 m, to facilitate the comparison between them.

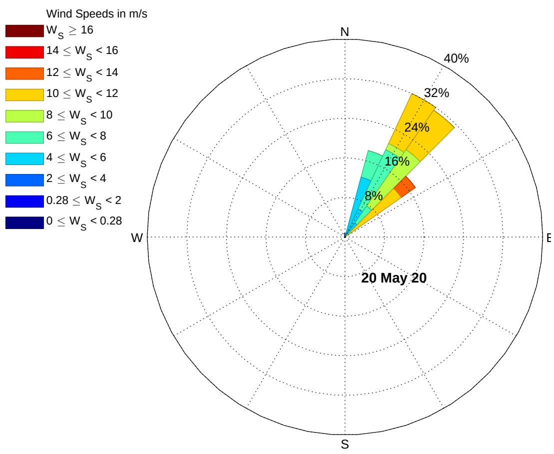
### 3.3.3 20th of May (day of nearly constant wind direction)

During the 20th of May the wind blew almost always from the same direction, Figure 3.13. These are are ideal operating conditions for a wind turbine, because it reduces the time needed to align wind turbines with the flow and also decreases maintenance costs associated with fatigue of the yaw mechanisms needed for such an alignment (Dai et al., 2017). Long periods of time with constant wind speed and wind direction are very useful for simulation purposes (Section 2.4).

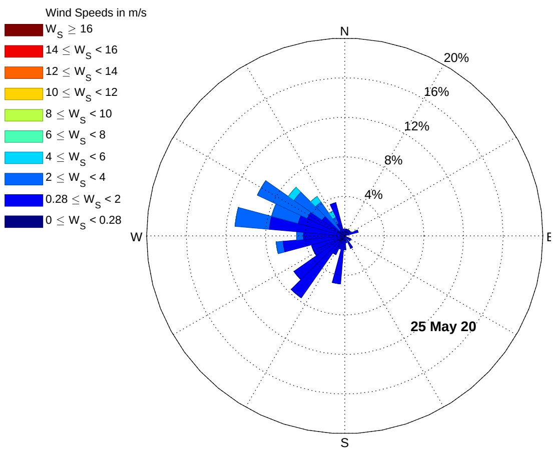
After searching for constant periods on the time series, it was found that the 20th of May has many such periods (see Section 2.4 for more information). This provides another reason for showing this day in greater detail.



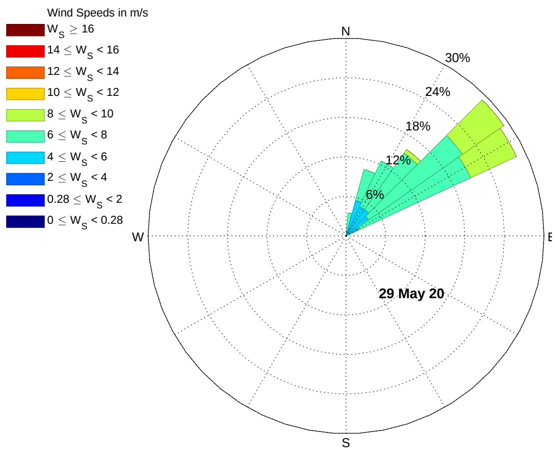

(a) 37/rsw06




(b) 20/tse04




(c) 25/tse09

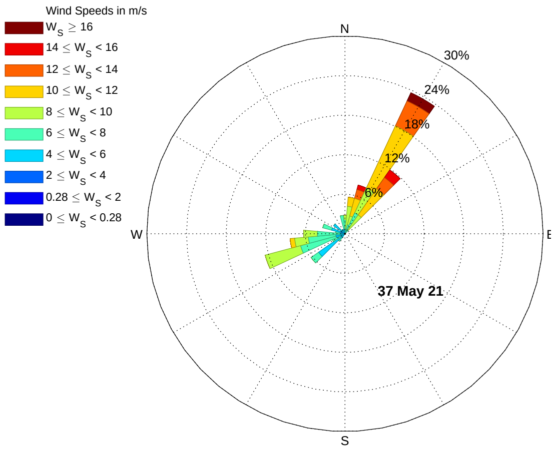



(d) 29/tse13

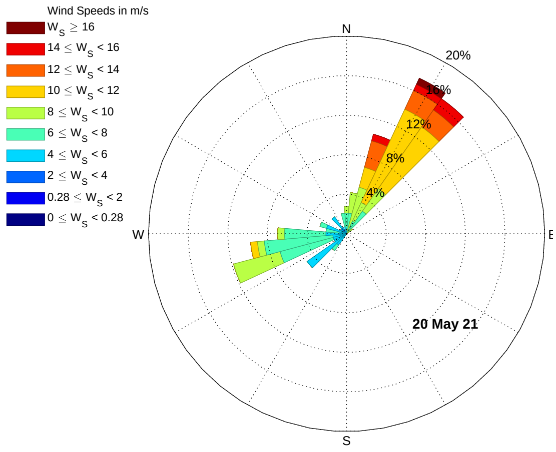
Figure 3.13: Wind roses of the 20th of May at 60 m

### 3.3.4 21st of May (day with highest wind speed in tower 37)

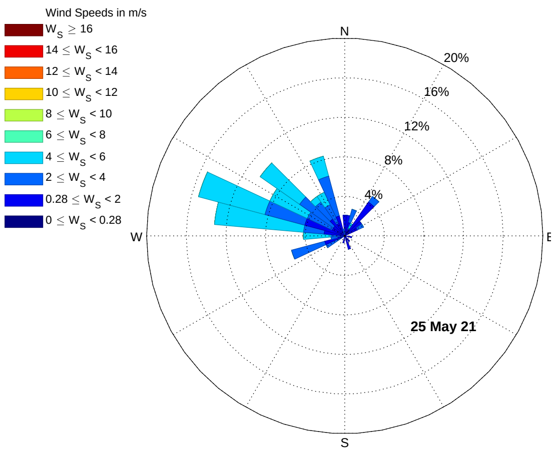
Figures 3.14 are the wind roses for the 21st of May for the 4 towers at 60 m (37, 20, 25 and 29, respectively). This day was chosen because it is the one which has the highest speeds recorded (in tower 37) in the period studied. Note that the 5th of May has higher wind speeds recorded, however the data for that day is incomplete and therefore it isn't reliable enough to be presented here.



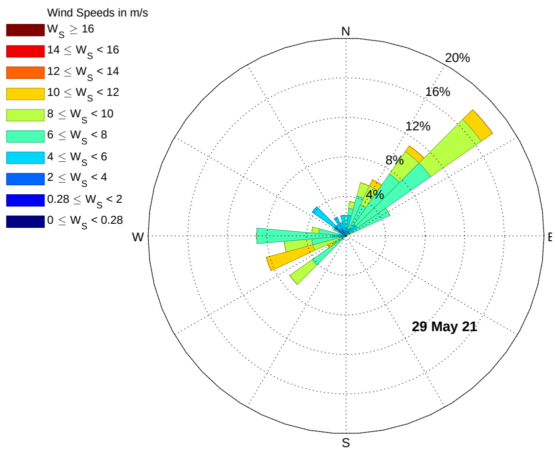

(a) 37/rsw06




(b) 20/tse04




(c) 25/trse09

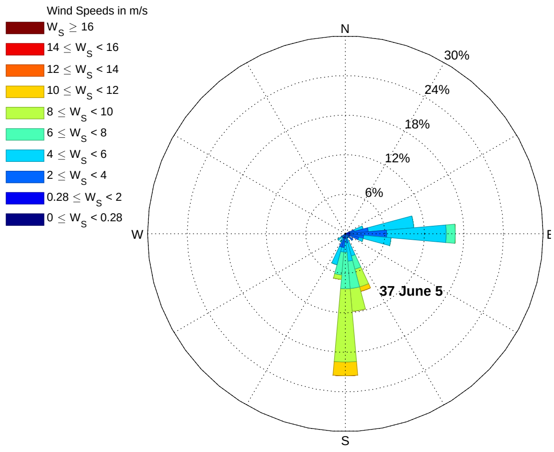



(d) 29/tse13

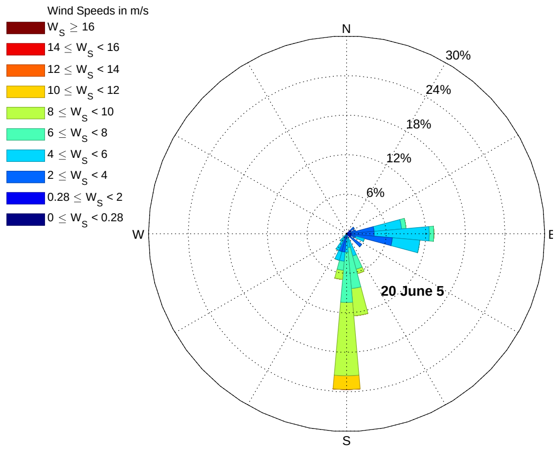
Figure 3.14: Wind roses of the 21st of May at 60 m

### 3.3.5 5th of June (day with unusual wind direction)

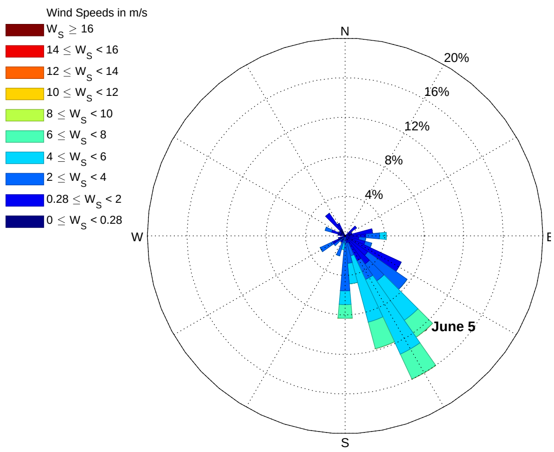
The wind roses for the 5th of June (Figure 3.15) are presented because they show that the two main wind directions for that day form an almost 90º angle, which is strange and may be evidence of an error, or errors, in the data set, although none were found using the criteria previously mentioned (Section 2.3.2). This may be one of those cases to be corrected using the new data sets that will become available. On the other hand it may be entirely correct and it is just the way the atmosphere behaved in that place that day.



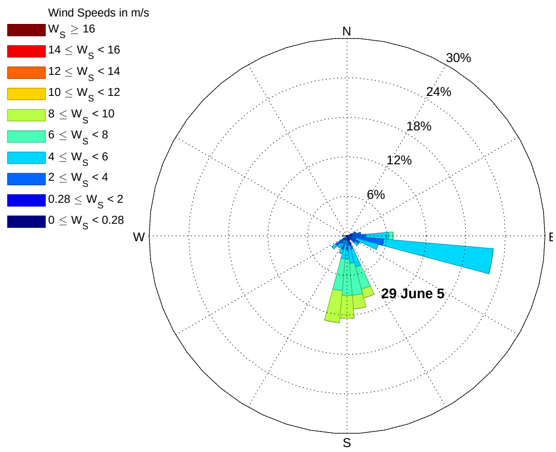

(a) 37/rsw06




(b) 20/tse04




(c) 25/tse09



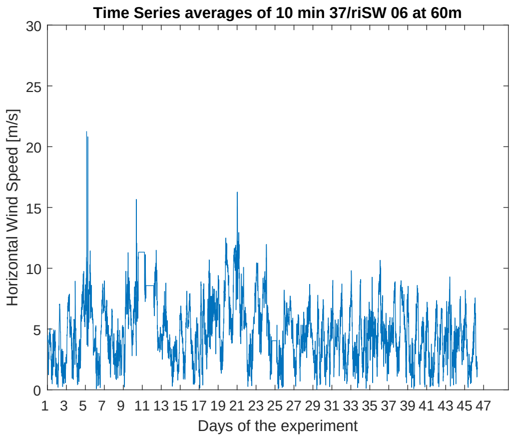

(d) 29/tse13

Figure 3.15: Wind rose of the 5th of June at 60 m

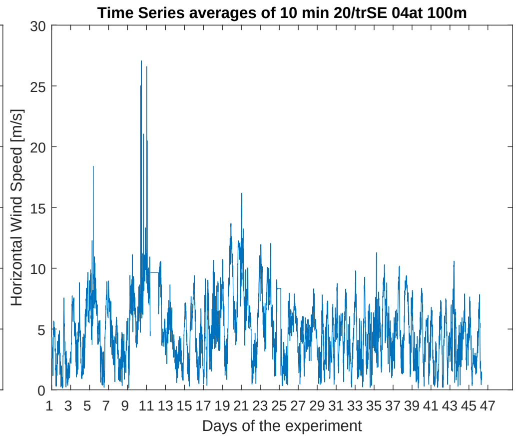
## 3.4 Time series

In this Section, an overall view of the atmospheric conditions is given via time series. It is shown how wind speed varied during those 46 days of the IOP (subsection 3.4.1) and also the behaviour of wind speed, direction and temperature during a set of particular days (subsections 3.4.2 – 3.4.9).

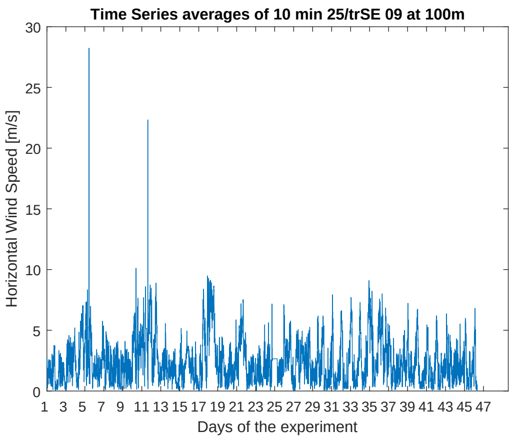
As in the case of the wind roses, the data refers to the same towers (37, 20, 25 and 29) and always to the topmost sonic anemometer, 60 m agl, in the case tower 37, and 100 m agl, in the case of towers 20, 25 and 29.



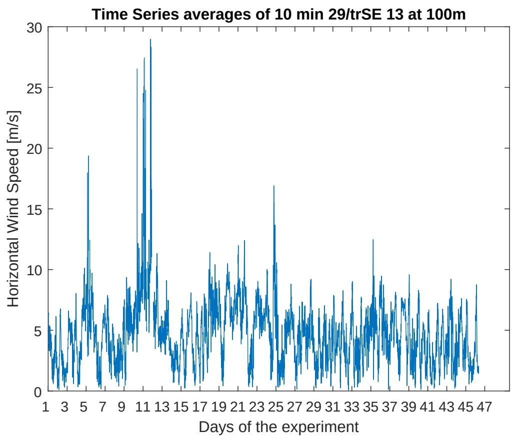

(a) 37/rsw06




(b) 20/tse04




(c) 25/tse09




(d) 29/tse13

Figure 3.16: Time series of 10 min averages (towers 20, 25 and 29 at 100 m, and tower 37 at 60 m)

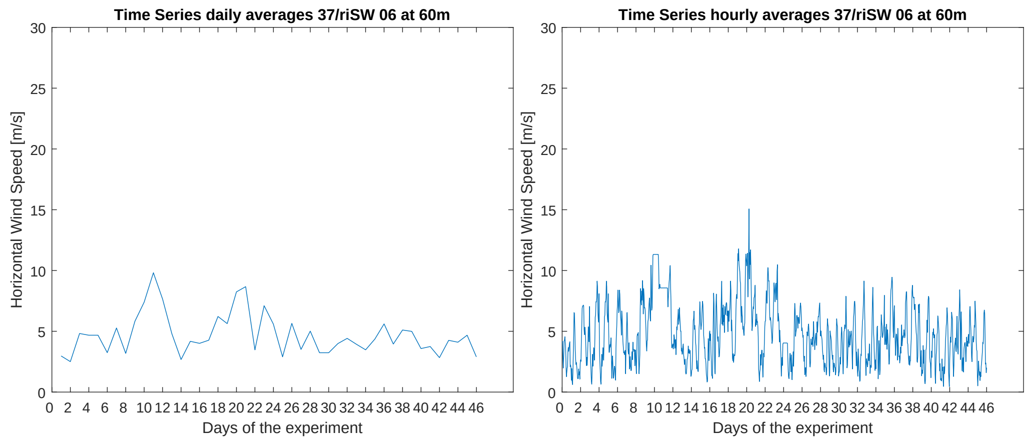
### 3.4.1 Time series for all days

By plotting all measurements (144 per day with 100% availability) into a single time series over the 46 days of the IOP, it can be easily seen that, for instance, the highest values were measured at towers 20 and 29 (Figures 3.16b and 3.16d) and at tower 25 (Figure 3.16c) the wind speed was lower. However, these figures are difficult to read, and therefore of little use. If the objective is to see the detail and variations every 10 min, data must be plotted per day; or if the objective is to see daily variations, plot the time series of the daily average or hourly averages, Figures 3.17a and 3.17b.

It was decided to plot the several variables along a single day for all days. This guarantees a good enough resolution without great loss of the bigger picture (Sections 3.4.2–3.4.9).

Figures 3.17 show that the wind speeds in towers 37, 20 and 29 are similar, throughout the experiment and also that mast 25, due to its location in the valley, is subjected to a different main flow and, therefore, has lower wind speeds. It is also possible to observe that the 5th, 11th, 12th, 21st, 23rd, 24th and 25th of May have the highest recorded wind speeds. A few thunderstorms (Table 3.1) occurred, which may explain some high spikes in wind speed. The occurrence of thunderstorms also accounts for several of the periods of time in which the data gathered is filled with errors, making an analysis of extreme weather conditions difficult.

The time series for tower 37 at 60 m of daily averages and hourly averages, Figure 3.17 are shown. These figures provide a quick view of the conditions of wind speed in all days, however, the averages greatly distort the individual measurements. These figures are not appropriate for an in depth analysis.




(a) Daily averages

(b) Hourly averages

Figure 3.17: Daily and hourly averages (tower 37 at 60 m)

The following subsections (3.4.2 – 3.4.9) illustrate a set of eight days, each with a feature that was found worth reporting, for instance, day with high wind speeds relative to the others of the IOP (instances of 10 m/s and higher) (subsection 3.4.6), low wind speeds ( 5 m/s and lower) (subsection 3.4.8), with poor data (subsection 3.4.4), with constant wind direction (subsection 3.4.3), as well as days with typical conditions (subsection 3.4.9).

Figures 3.18 3.25 display the daily variation of 10 min average wind speed, wind direction and temperature. The standard deviation and maximum appear in the legend and mean wind speed also as a line across the plot. Note that the maximum in the legend is the maximum of all maxima registered during 10 minutes (Section 2.3.2).

### 3.4.2 4th of May (day with stationary period and sharp change in wind speed and direction)

On the 4th of May in mast 20 (Figure 3.18) the wind speed shows a steady rise throughout the day until ≈20:00, when it sharply decreases, followed by a stationary period of both wind speed and wind direction, until ≈22:00. This sudden drop coincided with an abrupt change in wind direction. Such changes appear in several of the time series, but few are as sharp as this one. It can be seen that changes in direction accompany changes in wind speed (for instance at 08:00 and 20:00), although not always in the same way (sometimes the wind speed increases, others it decreases). Due to the swift changes in direction and low wind speeds, this is not a good day for wind energy applications.

The temperature is abnormally high in the night and early morning, when compared to other time series (e.g., see Figure 3.23). This also happens on the 9th of May (Figure 3.19) and 13th (Figure 3.24) of June, as well as others. This happened because the previous day had higher temperatures and the air could only cool down so much before the new sunrise.

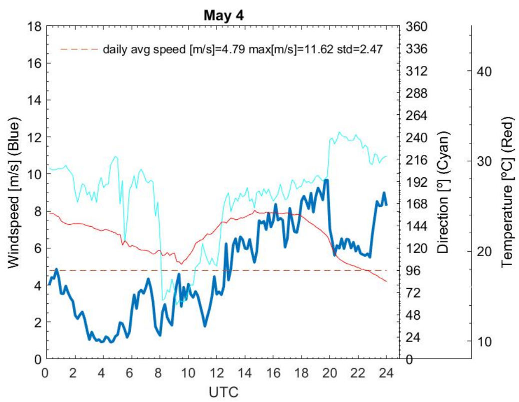



Figure 3.18: 4th of May (tower 20)

### 3.4.3 9th of May (day with constant wind direction)

During the 9th of May on mast 37, the wind blew almost always from the Southwest, Figure 3.19 and often with high values (up from 6 m/s) from 10:00 to the end of the day. In this case the wind direction also seems to accompany the wind speed, without a clear relation between the two, but only until approximately 17:20. This is a good day for wind energy applications, due to its nearly constant wind direction, although the period around 08:00 has lower speeds than $2\,m\,s^{-1}$.

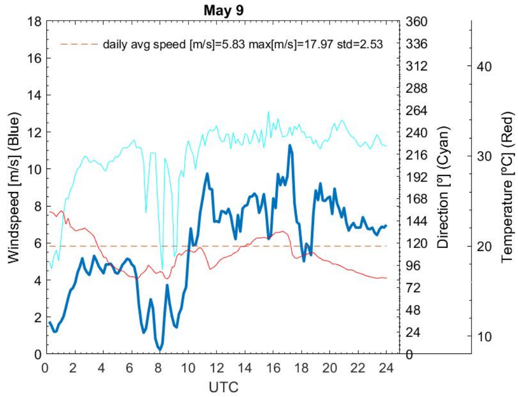



Figure 3.19: 9th of May (tower 37)

### 3.4.4 11th of May (worst day regarding data availability)

The 11th of May was is notorious in all towers for its data unreliability, Figure 3.20, by a large number of spikes and gaps in wind speed and temperature. These are due to removal of values greater than $30\,\mathrm{m\,s^{-1}}$ and $55\,°\mathrm{C}$. The horizontal lines from 15:00 to 17:00 are due to freezing of values. This day cannot be part of an analysis of the physical phenomena of the experiment, but it is of interest as an example of a "bad" day regarding data quality and as test for the data cleaning procedures.

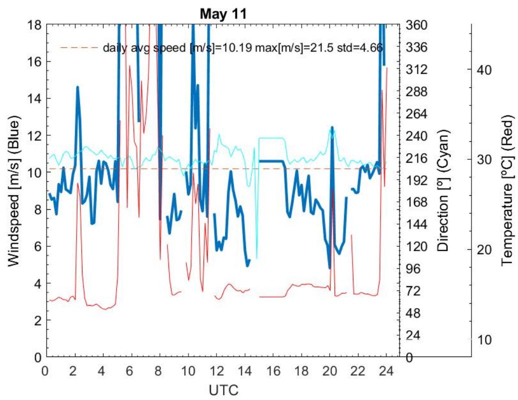
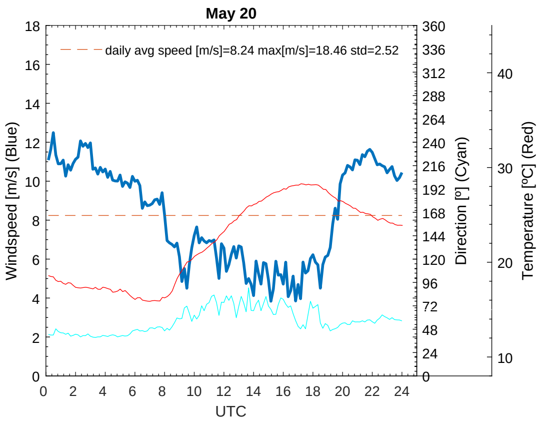
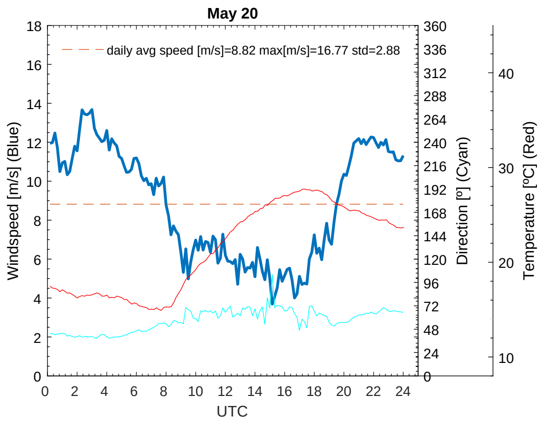



Figure 3.20: 11th of May (tower 29)

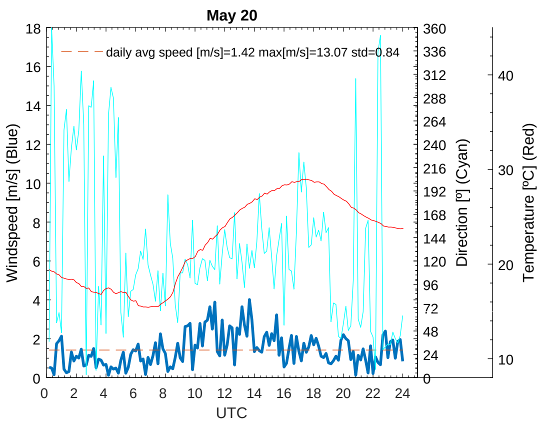
### 3.4.5 20th of May (day with many stationary periods and constant wind direction)



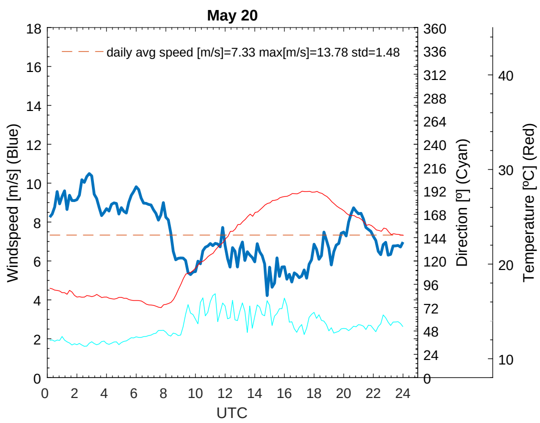

(a) 37/rsw06




(b) 20/tse04




(c) 25/tse09




(d) 29/tse13

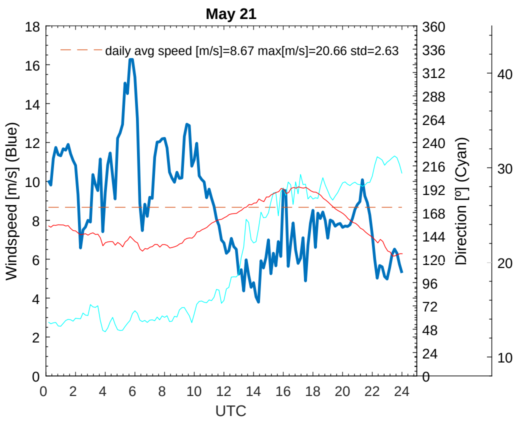
Figure 3.21: 20th of May

The 20th of May (Figure 3.21) is an important day, for not only does it have relatively high wind speeds, but also many periods that are good candidates for stationarity (see Section 2.4). Apart from mast 25 (Figure 3.21c), all the others exhibit a period of near constant wind speed between approximately 02:00 and 04:00. In mast 25, there also a period of near constant speed, but between 01:30 and 03:00.

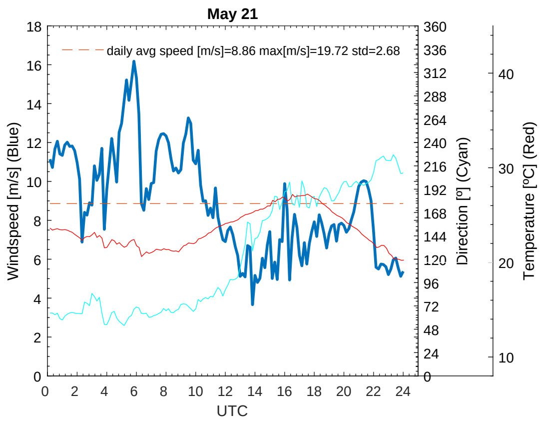
From approximatively 21:00 until 24:00 there is a long period of near constant speed on both towers 37 and 20 (Figures 3.21a and 3.21b) as opposed to mast 29 (Figures 3.21d). Because the wind direction was always from the northeast, it appears that the terrain influenced the flow in such a way as to create this period.

### 3.4.6 21st of May (day with highest wind speeds)

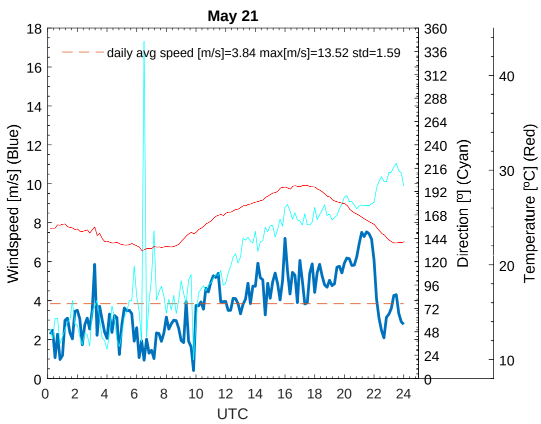
On the 21st of May, at mast 37 and 20 (Figures 3.22a and 3.22b) the change in direction from Northeast to South accompanies a decrease in wind speed. That trend seems to continue in mast 29 (Figure 3.22d), however the difference is less stark, with a great increase at 20:00. In mast 25 (Figure 3.22c) the trend is the opposite, i.e. the increase in wind direction accompanies an increase in wind speed.



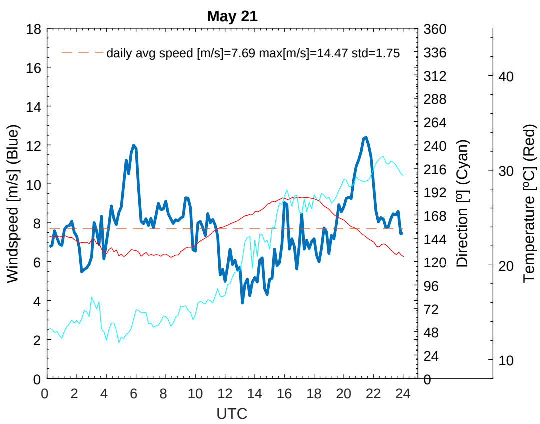

(a) 37/rsw06




(b) 20/tse04




(c) 25/tse09




(d) 29/tse13

Figure 3.22: 21st of May

The temperature follows the usual trend of lower values in the morning and night with a maximum in the afternoon (e.g., see Figure 3.23).

### 3.4.7 24th of May (day with great spike in wind speed)

The 24th of May at tower 29 (Figure 3.23) is a fairly normal day compared to the others of the IOP, apart from the huge increase in wind speed from 22:00 to 23:30. In one and half hours the wind speed increased from less than $3\,\mathrm{m\,s^{-1}}$ to more than $16\,\mathrm{m\,s^{-1}}$, an increase of more than 500%. Such a climb in such a short amount of time may be evidence of some error in the data gathering. On the other hand, this could have been a sudden wind gust, only by inspecting the data at 20 Hz can the real reason be discovered.

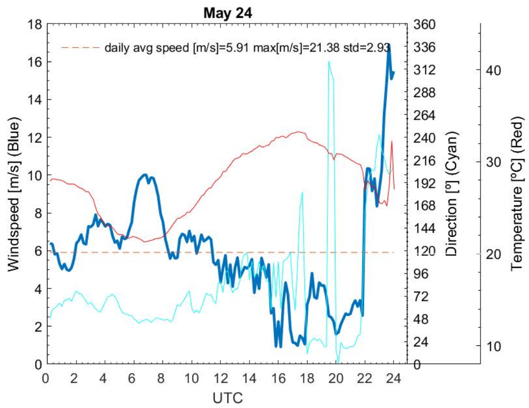



Figure 3.23: 24th of May (tower 29)

### 3.4.8 13th of June (day with low wind speeds)

The time series for the 13th of June at tower 25 (Figure 3.24) shows the typical low wind speeds recorded in this tower. The wind direction is erratic throughout the day. Such conditions are terrible for the wind energy industry, and further evidence that the valley is a poor location for a wind turbine. A relation between direction and wind speed seems apparent, given that, to almost every change in direction there is a corresponding change in wind speed. There is not, however a consistency, ie, sometimes the wind speed increases other it decreases, with the same change in direction (either to North or to South).

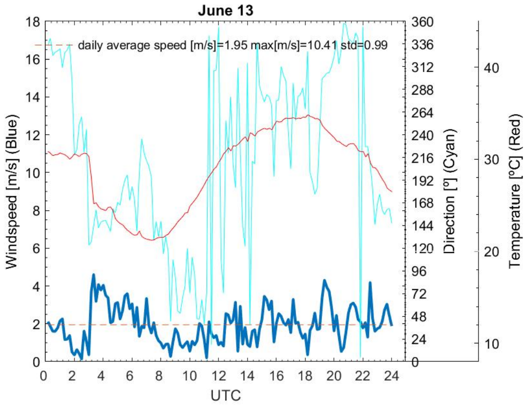
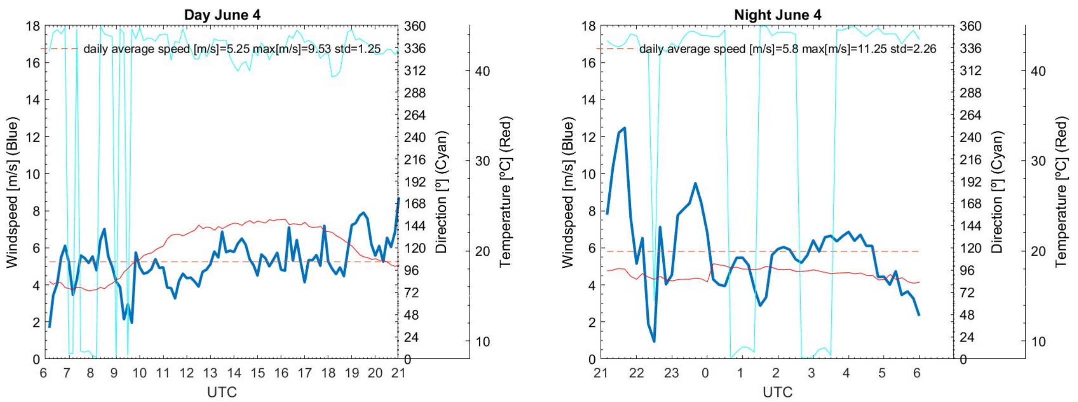



Figure 3.24: 13th of June (tower 25)

### 3.4.9 4th of June (day with typical conditions of day and night)

The average wind speed for all days at tower 29 at 100 m was of $4.85\,\mathrm{m\,s^{-1}}$, this is a very coarse parameter, but it gives an idea of the typical conditions in that tower. To show an example of a typical day, the time series of nighttime and daytime of the 4th of June are presented (Figure 3.25), a day which has average speed close to $4.85\,\mathrm{m\,s^{-1}}$. The separation of both periods into two Figures allows for a zoomed in view, useful for a closer study.




(a) Day (b) Night

Figure 3.25: Daily and nightly time series at tower 29

It can be seen in Figure 3.25a that both the wind speed and direction experienced very little deviation from its average value. The temperature starts at a lower value at night then climbs (sunrise) to its maximum of approximately 25ºC then starts to descend again (sunset). This behaviour is consistent with most of the other time series (e.g., see Figure 3.23).

At night (Figure 3.25b) the temperature has a much steadier curve, however the wind speed shows great variation at the beginning of the night. The wind direction remains constantly from the North (the great spikes are due to initial data gathered; when the wind flow exceeds 360° it goes back to 0; both directions correspond to North).

It is worth mentioning that, on most of the time series, there is no distinct difference in wind speed between night and day. In some the highest wind speeds occur during daytime (e.g., see Figure 3.19), in others during nighttime (e.g., see Figure 3.23). This day was one of the latter cases.

## 3.5 Flow stationarity

In order to discover stationary periods that can be used as comparison with computer models, it was necessary to obtain methods of evaluating the stationarity of such periods. The first method was visual inspection, followed by the tools presented in Section 3.5.2.

### 3.5.1 Visual inspection

By visual inspection of the wind speed and direction of time series, 17 days were identified with periods during which the stationarity condition can be valid (Table 3.13).

| # | Day | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| 1 | 3 May | 03:00–08:00 | | | |
| 2 | 4 May | 20:00–22:00 | | | |
| 3 | 9 May | 21:00–23:00 | | | |
| 4 | 7 May | 02:00–04:00 | | | |
| 5 | 15 May | 04:00–08:00 | | | |
| 6 | 19 May | 05:00–08:00 | 20:00–23:00 | | |
| 7 | 20 May | 03:00–06:00 | 06:00–08:00 | 10:00–12:00 | 20:00–24:00 |
| 8 | 21 May | 00:00–02:00 | | | |
| 9 | 22 May | 02:00–06:00 | | | |
| 10 | 23 May | 06:00–09:00 | | | |
| 11 | 26 May | 15:00–17:00 | 20:00–22:00 | | |
| 12 | 5 June | 14:00–18:00 | | | |
| 13 | 6 June | 14:00–18:00 | | | |
| 14 | 7 June | 04:00–08:00 | 20:00–24:00 | | |
| 15 | 8 June | 14:00–18:00 | | | |
| 16 | 9 June | 15:00–18:00 | | | |
| 17 | 15 June | 15:00–19:00 | | | |

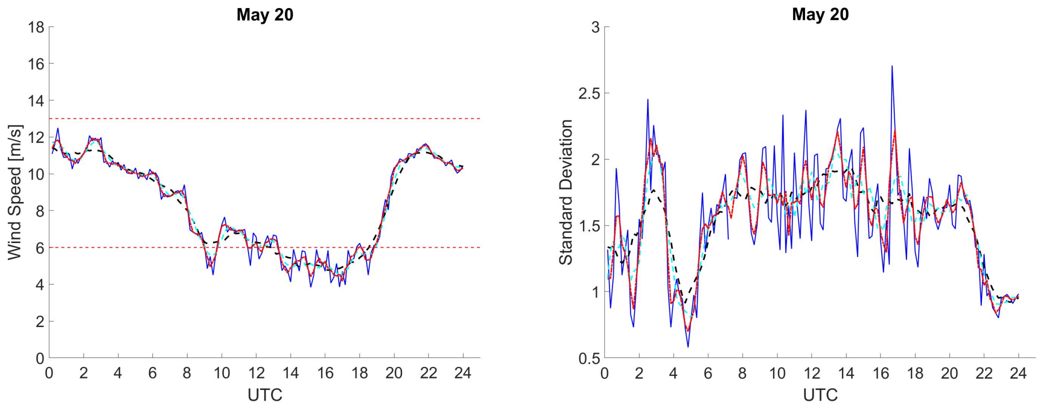
Table 3.13: Days with potential stationary periods (visual inspection).

From this, a total of 72 (432 periods of 10 min) hours were discovered as candidates for stationarity.

### 3.5.2 Graphic methods: moving averages

Moving averages (2.3) are most appropriate for analysis of non-stationary time-series (e.g. (Bendat and Piersol, 2000)). For determining the averaging window size which better fit the evolution of the variables, three values were considered: 2 hours, 1 hour and 30 minutes (12, 6 and 3 sets of 10 minutes), providing a large (12 points), a moderate (6 points) and a fine (3 points) smoothing of the original data.

Figures, 3.26–3.28 show the plots of the time series of the 10 minute averages and standard deviation for those averages, superimposed with the moving averages of that variable (speed, direction and temperature) for the 20th of May.



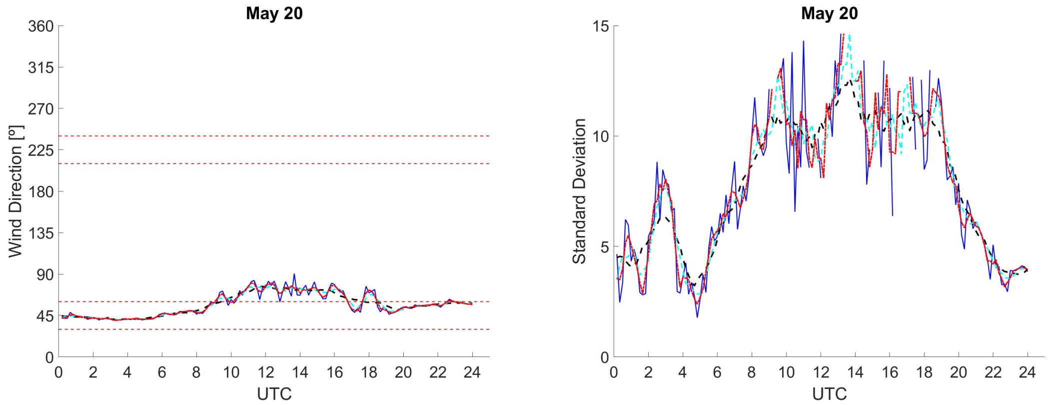

(a) 10 min averages (b) Standard deviation

Figure 3.26: Wind speed, 20th of May Blue: original data, 10 minute averages; cyan: 6 point moving average; red: 3 point moving average; black: 12 point moving average

The horizontal lines in figures 3.26–3.27 show the wind speed and direction intervals for stationary flows, as defined in Section 2.4. These figures were made for all of the 17 days signaled, however, in the interest of simplicity, only one day is presented here.

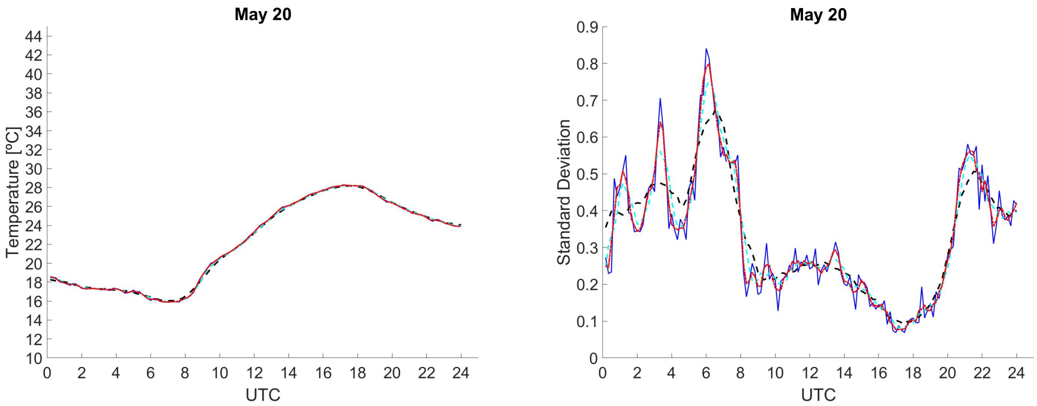
By closely observing the figures of wind speed, such as 3.26, it was concluded that the 30 minute average (3 points) was the appropriate window size, since it smoothed the time series without shifting the locations of maxima and minima, as was the case with 6 and 12 point window (Figure 3.29). On a second approach, the observation of the other variables yielded the same result. It was found that the standard deviation can vary greatly from one average to the next within constant periods. Because of this, the moving averages of the standard deviation of the 10 minute averages are not good criteria for stationarity.

In the next section the time series of Section 3.4 are repeated, but with moving averages with a window of 3 points, and only for some of the 17 days signalled.




(a) 10 min averages (b) Standard deviation

Figure 3.27: Direction, 20th of May Blue: original data, 10 minute averages; cyan: 6 point moving average; red: 3 point moving average; black: 12 point moving average




(a) 10 min averages (b) Standard deviation

Figure 3.28: Temperature, 20th of May Blue: original data, 10 minute averages; cyan: 6 point moving average; red: 3 point moving average; black: 12 point moving average

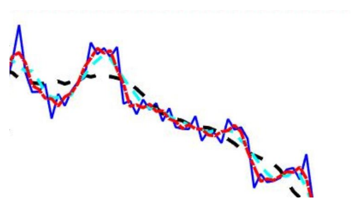


Figure 3.29: Zoom of moving averages (zoom of the left part of Figure 3.26 approximately from 00:30 to 7:00) blue: original data, 10 minute averages; cyan: 6 point moving average; red: 3 point moving average; black: 12 point moving average

### 3.5.3 Graphic methods: time series of moving averages

Figures 3.30–3.34 show some moving averages with a window of 3 points (30 minutes) of the wind speed, direction and temperature, as well as the corresponding standard deviation, for 5 of the 17 days identified. These smoothed curves provide a more immediate view of the plateaus needed to identify the stationary periods. They also present a more rigorous way of performing visual identification. The window chosen for wind speed was adopted for the other variables, since it was considered to provide the best fit.

Figures like 3.30–3.34 were used, in addition to the figures of the several superimposed averages, such as Figure 3.26, and the tables of moving averages, to correct the time periods initially discovered. The resulting time periods are presented in the next Section (3.5.4).

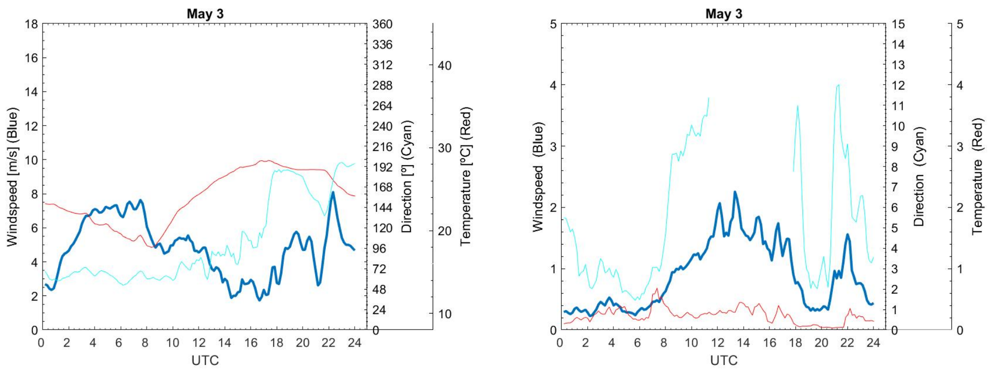



Figure 3.30: May 3 3 point window moving mean of 10 minute averages (left) and their standard deviation (right)

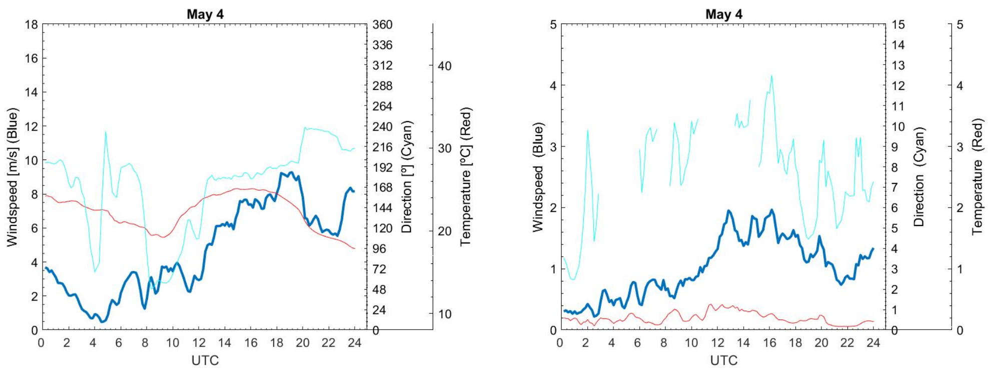



Figure 3.31: May 4 3 point window moving mean of 10 minute averages (left) and their standard deviation (right)

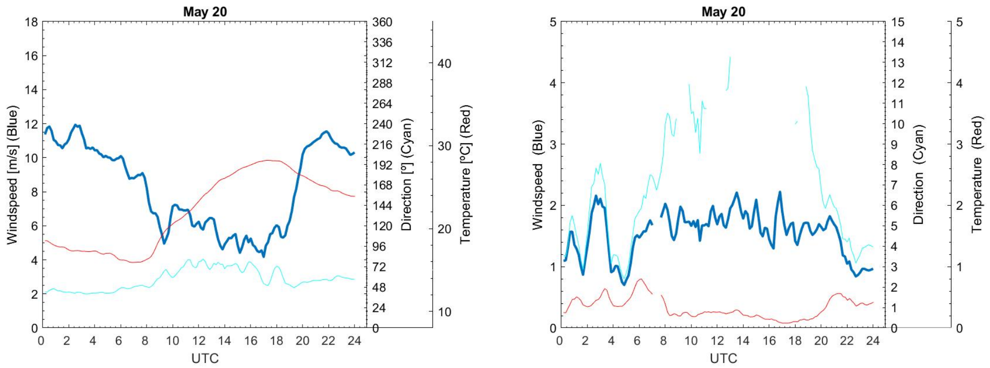



Figure 3.32: May 20 3 point window moving mean of 10 minute averages (left) and their standard deviation (right)

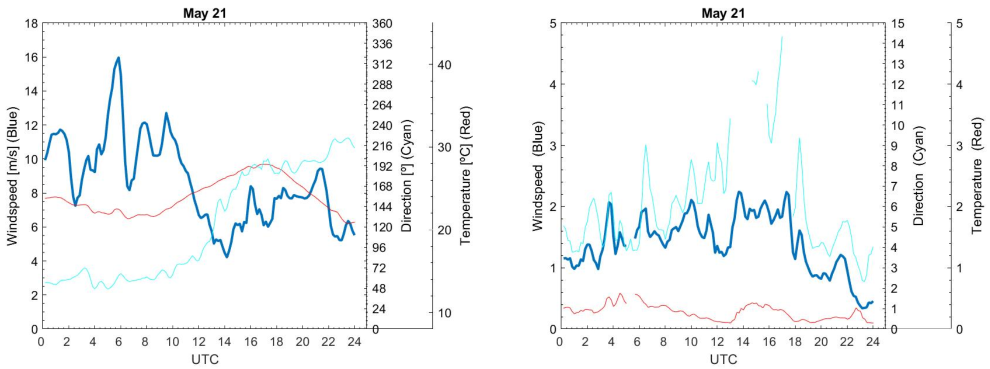



Figure 3.33: May 21 3 point window moving mean of 10 minute averages (left) and their standard deviation (right)

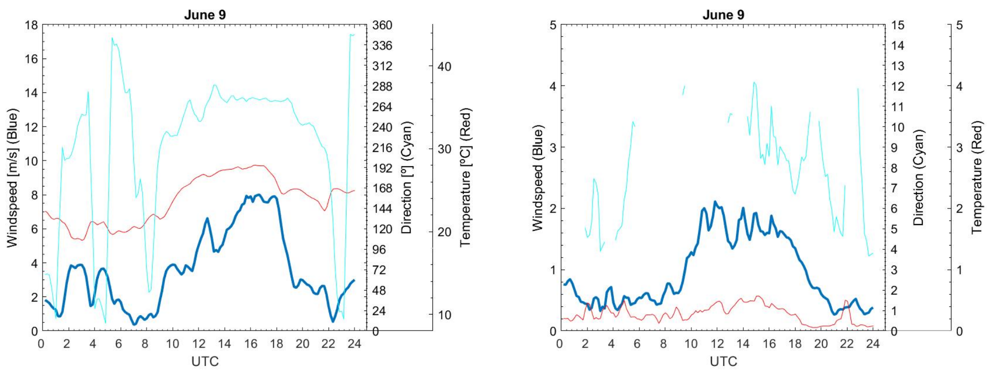



Figure 3.34: June 9 3 point window moving mean of 10 minute averages (left) and their standard deviation (right)

### 3.5.4 Tables with stationary periods

The search for stationarity periods was guided by two criteria:

1. difference ($\delta\phi$) between 10 minute average (2.1) lower than 5, 4, 3 or 2% and the number of consecutive periods greater than 3 or 6 (30 min or 60 min long);

2. difference ($\delta\tilde{\phi}$) between moving averages (2.2) with windows ($m$) of 3 points (half an hour) or 6 points (one hour), lower than 5, 4, 3 or 2% and the number of consecutive periods greater than 6 (60 min long).

By visual inspection and trial-and-error of the many combinations of $\delta\tilde{\phi}$ and $m$, it was concluded that the best criterion would be $m = 2$ and $\delta\tilde{\phi} = 2\%$, or the in case of failure, a less restrict criteria of $m = 2$ and $\delta\tilde{\phi}$ =3% or $m = 6$ and $\delta\tilde{\phi} = 2\%$. Table 3.14 is the result of criterion ($m = 2, \delta\tilde{\phi} = 2\%$).

| | | Beginning | | | End |
|---|---|---|---|---|---|
| | $N_{10}$ | Day | Hour | Day | Hour |
| | 6 | 7 May | 23:50 | 8 May | 00:50 |
| | 6 | 15 May | 04:10 | 15 May | 05:10 |
| | 10 | 15 May | 23:50 | 16 May | 01:30 |
| | 6 | 19 May | 05:00 | 19 May | 06:00 |
| | 17 | 20 May | 03:10 | 20 May | 06:00 |
| | 6 | 20 May | 06:30 | 20 May | 07:30 |
| | 7 | 20 May | 20:00 | 20 May | 21:10 |
| | 12 | 20 May | 22:00 | 21 May | 00:00 |
| | 6 | 21 May | 00:30 | 21 May | 01:30 |
| | 7 | 21 May | 19:10 | 21 May | 20:20 |
| | 9 | 21 May | 22:40 | 23 May | 00:10 |
| | 12 | 23 May | 06:00 | 23 May | 08:00 |
| | 6 | 23 May | 23:10 | 24 May | 00:10 |
| | 6 | 26 May | 15:30 | 26 May | 16:30 |
| | 6 | 26 May | 19:40 | 26 May | 20:40 |
| | 6 | 7 June | 21:00 | 7 June | 22:00 |
| | 9 | 7 June | 23:30 | 8 June | 01:00 |
| Total | 137 | | | | |

Table 3.14: Number of 10 min periods, with 3 point moving averages differing by less than 2%

Table 3.15 shows the stationary periods for the 16 days corrected with the tables.

It can be seen that most of the time periods in Table 3.13 were shortened, but are still present and that the 15th of June disappeared entirely (therefore appearing only 16 days). The new procedure, not only validated the initial observation but also revealed new periods of stationarity.

In summary, a total of 34 periods of stationarity were identified (Table 3.15, being 23 northeasterly, 6 southwesterly and 5 from other directions.

| Day | Time Period | NE | SW | - | Speed | Dir | Temp |
|---|---|---|---|---|---|---|---|
| May 3 | 3:30-4:50 | ≈ x | | | 7.05 | 67.07 | 20.84 |
| | 5:30-7:20 | ≈ x | | | 7.15 | 59.18 | 19.24 |
| May 4 | *20:20-21:20 | | x | | 6.29 | 236.07 | 19.82 |
| May 7 | 2:10-3:40 | x | | | 6.62 | 56.91 | 17.09 |
| | 7:00-8:10 | ≈ x | | | 6.11 | 60.16 | 16.73 |
| May 9 | 21:20-22:20 | | x | | 7 | 229.51 | 17.03 |
| | 22:30-23:40 | | x | | 6.72 | 228.33 | 16.5 |
| May 15 | 4:10-5:10 | x | | | 5.94 | 54.36 | 19.98 |
| | *4:10-5:50 | x | | | 6 | 57.69 | 19.71 |
| May 19 | 5:20-6:20 | ≈ x | | | 8.88 | 34.02 | 11.99 |
| | *21:40-22:40 | ≈ x | | | 7.7 | 29.59 | 19.55 |
| May 20 | 3:10-6:00 | x | | | 10.2 | 42.08 | 16.9 |
| | 6:30-7:30 | x | | | 8.89 | 48.53 | 15.92 |
| | 20:00-21:00 | x | | | 10.8 | 54.77 | 25.77 |
| | 22:00-00:00 | x | | | 10.6 | 58.45 | 24.24 |
| May 21 | 00:30-1:30 | x | | | 11.58 | 54.88 | 23.87 |
| | 19:10-20:20 | | ≈ x | | 7.76 | 192.31 | 25.17 |
| May 23 | 6:00-8:00 | x | | | 10,09 | 48,79 | 22,02 |
| | 23:10-00:00 | x | | | 8,57 | 49,69 | 28,80 |
| | *2-3:20 | x | | | 8,26 | 39,92 | 24,74 |
| May 26 | 15:30-16:30 | | ≈ x | | 5,58 | 252,38 | 24,87 |
| | 19:40-20:40 | | x | | 9,95 | 244,52 | 20,81 |
| June 5 | 13:40-15:10 | | | x | 8,42 | 270,93 | 24,09 |
| | *14:00-16:10 | | | x | 8,53 | 270,48 | 24,11 |
| June 6 | *3:50-5:10 | | | x | 4,87 | 273,1 | 17,58 |
| June 7 | 21:00-22:00 | ≈ x | | | 8,36 | 25,04 | 30,62 |
| | *04:40-6:00 | x | | | 7,76 | 36 | 22,36 |
| | *6:10-7:30 | x | | | 8,34 | 43,15 | 21,77 |
| | *21:00-23:00 | ≈ x | | | 8,52 | 26,64 | 30,45 |
| June 8 | 4:10-5:10 | x | | | 6,89 | 49,65 | 27,81 |
| | *2:50-4:10 | x | | | 6,81 | 47,8 | 27,58 |
| | *6:50-8:10 | x | | | 5,47 | 52,46 | 24,36 |
| June 9 | 16:10-17:50 | | | x | 7,81 | 261,93 | 27,40 |
| | *15:20-17:40 | | | x | 7,79 | 258,97 | 27,61 |
| | Total | 23 | 6 | 5 | | | |

Table 3.15: Stationary periods (days, duration, wind speed, direction and temperature). *, if based on a 6 point moving average; ≈ exceeds the 15° criterion slightly.

## 3.6 Profiles of wind speed, direction and temperature

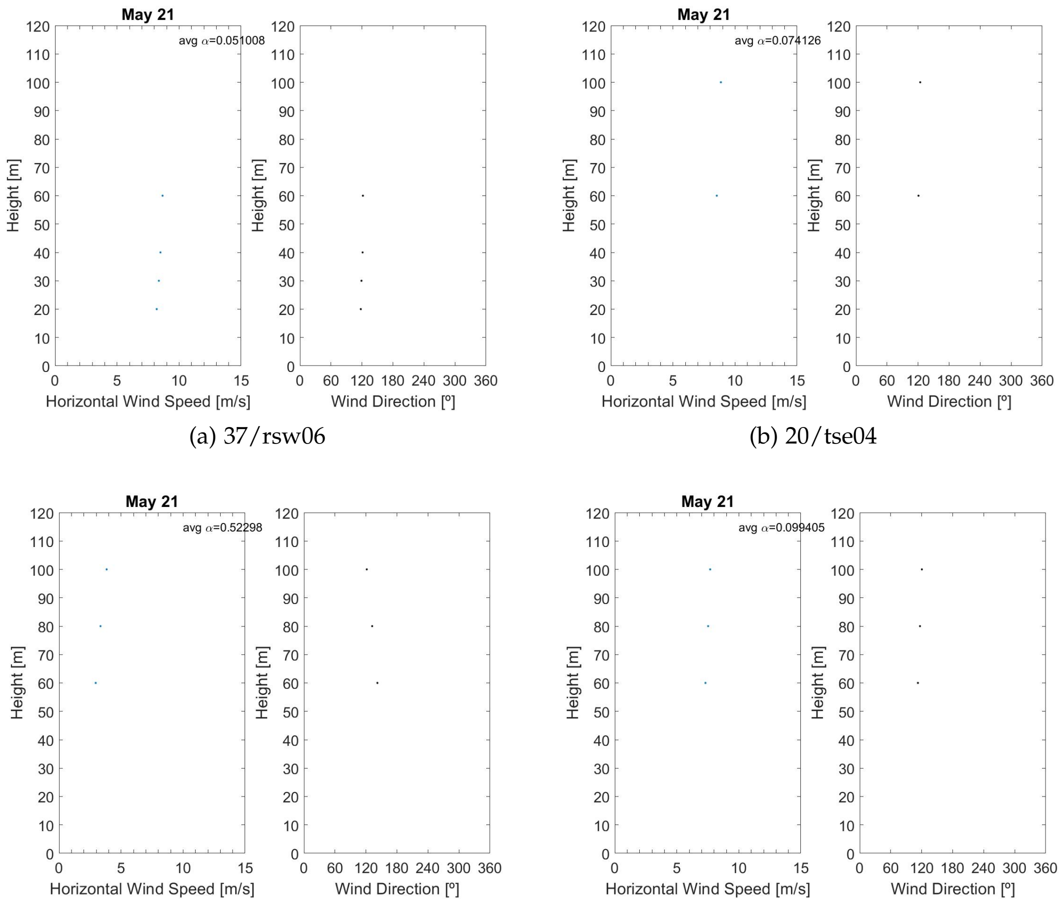
### 3.6.1 Towers' profiles

It can be seen that in the wind speed and direction profiles (Figures 3.35a and 3.35c) the wind speed increases with the distance to the ground, although not by much because of the small differences in height between measurements (only 20 metres). Tower 25 has the largest rotation of the flow with height, although it is still only of approximately 20 to 30°.

The shear factor ($\alpha$)is defined as:

$$\overline{V_H} = \overline{V_{ref}} \times \left(\frac{H}{H_{ref}}\right)^{\alpha} \tag{3.1}$$

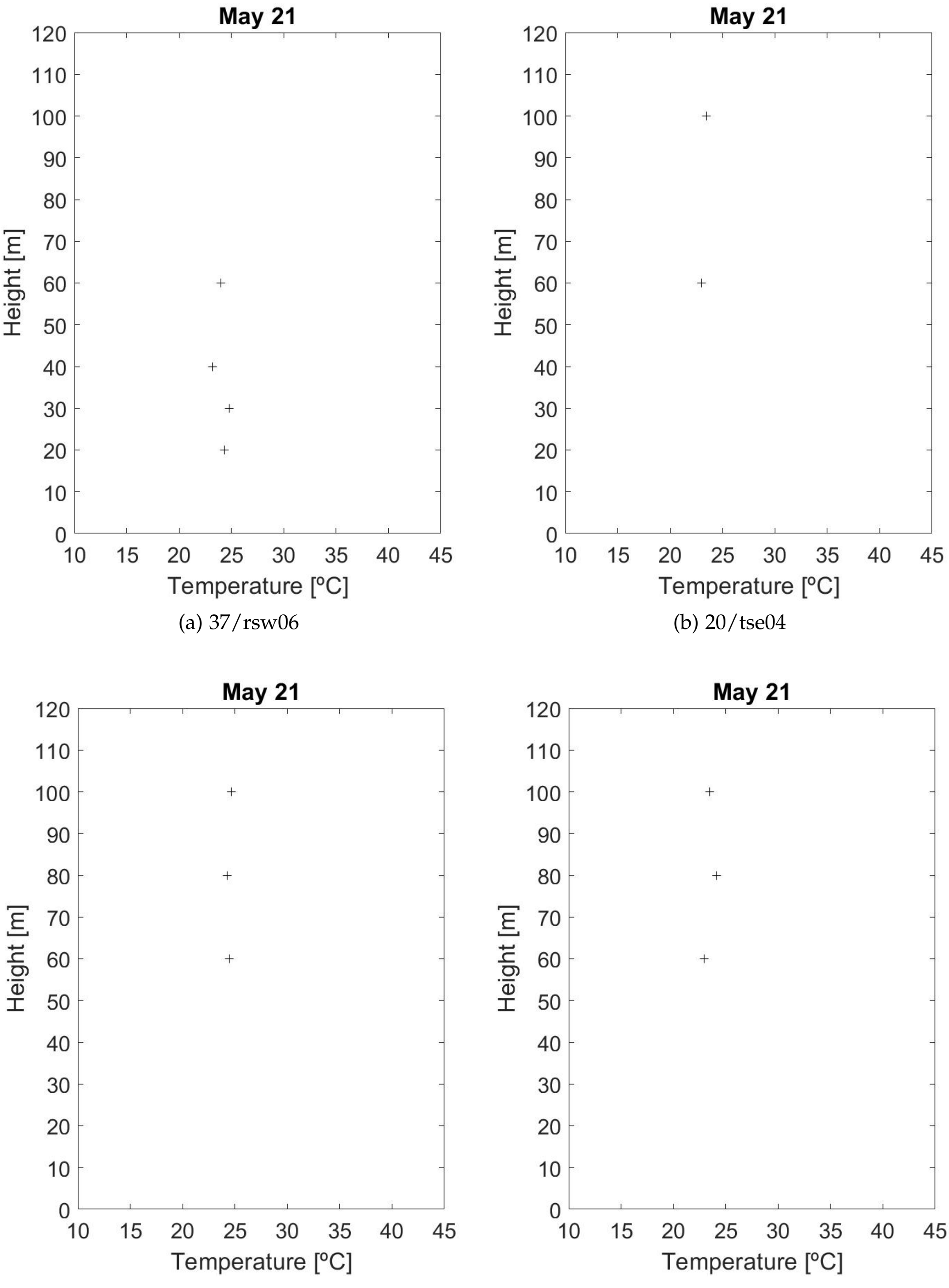
where $\overline{V_H}$ is the mean wind speed at height $H$ and $\overline{V_{ref}}$ is the mean wind speed at the reference height $H_{ref}$. Concerning wind energy applications, ideally, the $\alpha$ is always lower than 0.2. This is the case for all towers, except for tower 25, such different behaviour can be due to its lower wind speeds.




(a) 37/rsw06 (b) 20/tse04

(c) 25/tse09 (d) 29/tse13

Figure 3.35: Wind speed and direction profiles for all towers (May 21))




(a) 37/rsw06

(b) 20/tse04

(c) 25/tse09

(d) 29/trSE13

Figure 3.36: Temperature profiles for all towers (May 21)

### 3.6.2 Remote sensors' profiles

Wind speed, direction and temperature profiles for the three remote sensors are in Figures 3.37–3.40. Because the data are organized by 30 minute averages (Section 2.3), the profiles are a small part of the entire set. The data sets from station 122 did not include temperature.

#### 21st of May at 14:00

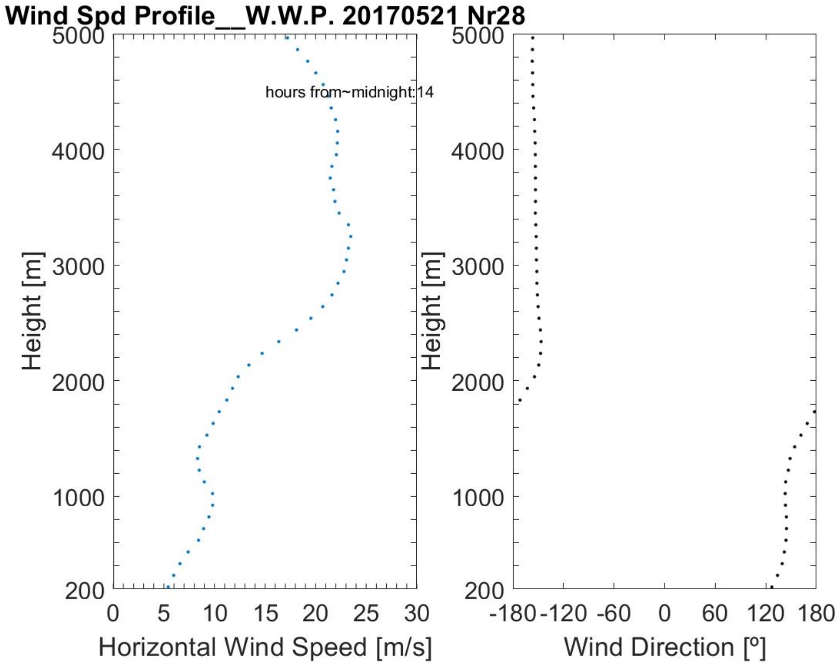
The 21st of May (Figures 3.37–3.38) the one with the highest recorded wind speeds. The hour being shown (14:00) has a full set of data for wind speed and direction, without gaps or errors.

Both x and y scales (terrain elevation or height above sea level, a.s.l.) are not the same for all of the sensors, due to the different formats of the data.

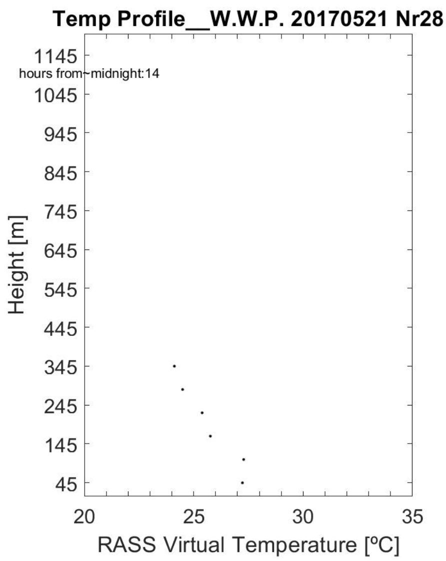
The more abrupt changes in wind speed and/or direction can be evidence of different layers and/or wind flows on the atmosphere. The wind direction veers constantly from its initial value from one height to the next, leading to a cumulative change of about 90° in station 121 (Figure 3.37) and 100° in station 122 (Figure 3.39). The changes in station 123 (Figure 3.38) are much lower, because its maximum measuring ceiling is much lower than the other two.

The influence of the terrain on the wind flow decreases rapidly with height and can be considered as non-existent at approximately 1000 m of altitude (Landberg, 2015). In order to study how the ridges and valley of Perdigão affect the wind flow, a greater focus must be dispensed between ground level and 1000 m.

In Figures 3.37 and 3.39 it can be seen that, at 1000 m, the wind speed lowers from approximately 10 $\mathrm{m\,s^{-1}}$ to 6.8 $\mathrm{m\,s^{-1}}$ and the wind direction changes approximately from 150º to 180º. This shows that the terrain slowed the wind flow and caused it to veer towards the south.

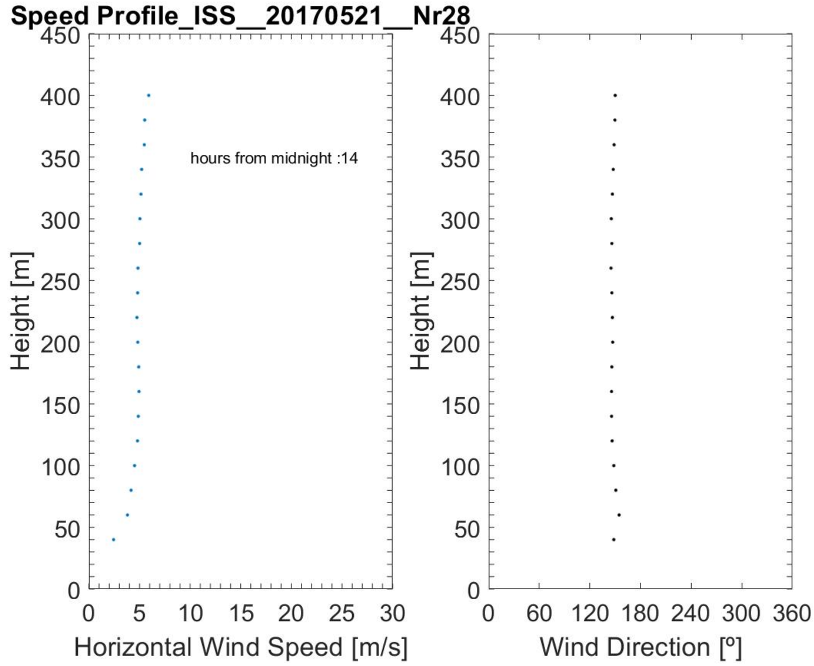



(a) Wind speed and direction

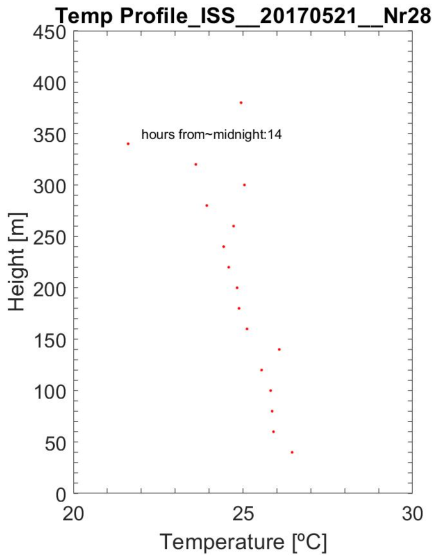



(b) Temperature

Figure 3.37: May 21; 14:00 UTC at station 121, radar wind profiler & RASS (NCAR)




(a) station 123




(b) Temperature station 123

Figure 3.38: Wind speed and direction (May 21; 14:00 UTC) at station 123, Sodar-RASS (NCAR)

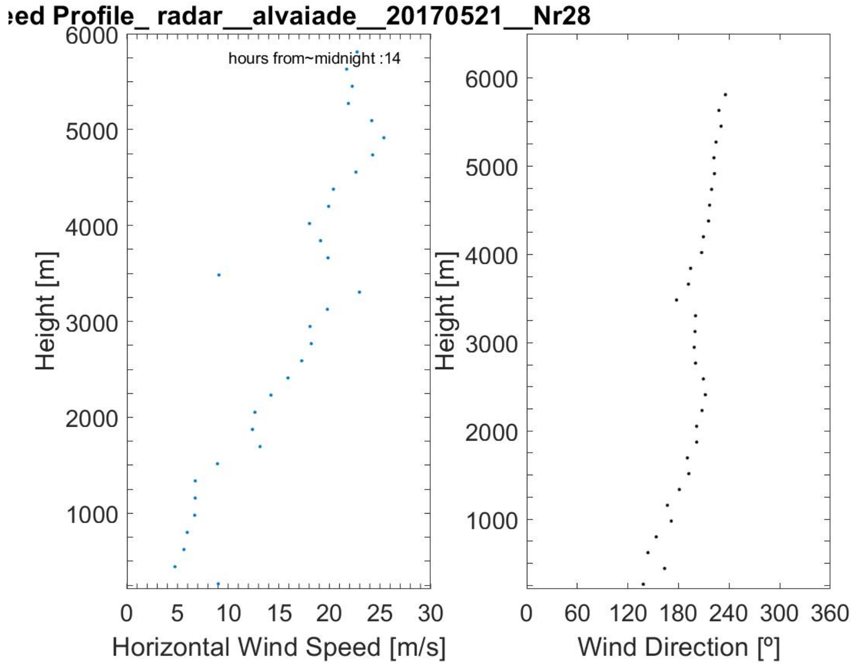
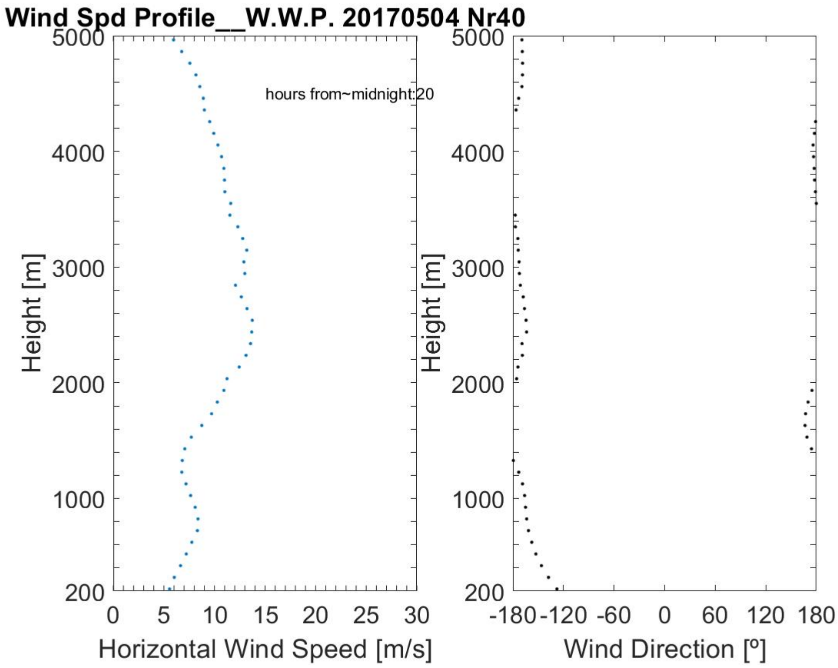



Figure 3.39: Wind speed and direction profiles (May 21; 14:00 UTC) at station 122, radar wind profiler (NCAR/NCAS)

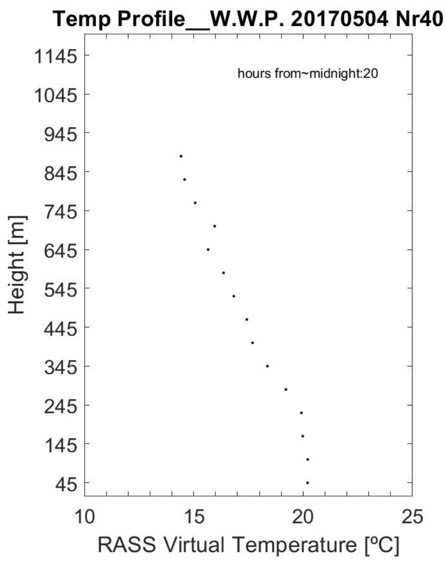
**4th of May from 20:00 to 21:30**

May 4th was identified as having a constant period from 20:20 to 21:20 (see Table 3.15), therefore the profiles from 20:00 to 21:30 (Figures 3.40 and .3–.13) are shown, in order to demonstrate the evolution of the flow throughout the site, in a period considered as constant. The flow has a southeast nortwest direction, therefore the profiles are presented in that order (from station 121 to 122). It is useful to have data regarding the 3 points of the flow (approach to the ridges, passing over it and exiting) since it can be compared to simulations.

Tables 3.16 and 3.17 show that the wind speed suffered changes much greater than 2% between each set of 30 min. The data regarding tower 37 do not possess such high values for the differences. This can be attributed to a number of factors such as the influence the terrain exerts over the flow (tower 37 on top of a ridge, while station 121 is on the terrain before it) and the different reliabilities of the sensors (sonic anemometers vs Profiling RADAR - RASS).




(a) Wind speed and direction




(b) Temperature

Figure 3.40: May 4; 20:00 UTC at station 121, radar wind profiler & RASS (NCAR)

| | 121 | | | 122 | |
|---|---|---|---|---|---|
| Time | Speed | Angle | Temp | Speed | Angle |
| 20:00 | 7.7 | 195 | N/A | 7.5 | 355 |
| 20:30 | 9.0 | 182 | N/A | 7.5 | 355 |
| 21:00 | 4.5 | 200 | 13.5 | 8.0 | 355 |
| 21:30 | 6.1 | 210 | 13.5 | 8.0 | 355 |

Table 3.16: Wind speed and wind direction, and temperature at 1000 m

| | 121 | | | | 123 | | 122 | |
|---|---|---|---|---|---|---|---|---|
| Time | Speed | Angle | Temp | Speed | Angle | | | |
| 20:00 | 6.7 | 210 | 17.7 | 11.5 | 185 | N/A | 6.6 | 350 |
| 20:30 | 6.7 | 210 | 16.1 | 7.0 | 220 | 17.1 | 6.7 | 355 |
| 21:00 | 5.8 | 230 | 16.4 | 6.8 | 240 | N/A | 6.4 | 350 |
| 21:30 | 5.9 | 225 | 15.5 | 7.0 | 242 | N/A | 6.4 | 355 |

Table 3.17: Wind speed and wind direction, and temperature at 400 m

## 3.7 Atmospheric stability 4th of May

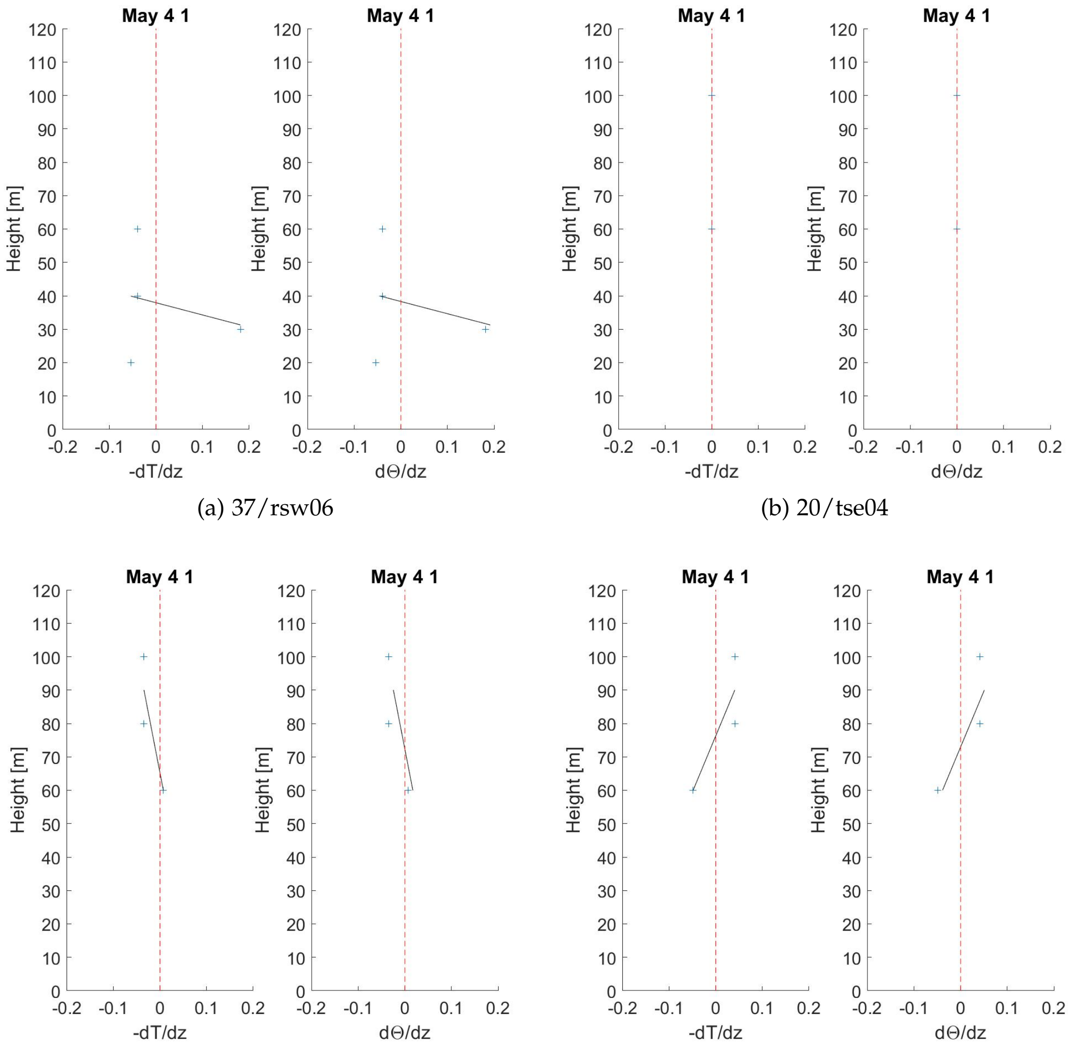
Figures 3.41–3.44 show the profiles of the variation of both temperature and potential temperature with height for the towers on the 4th of May, from 20:00 to 21:30. Figures 3.45–3.47 do the same for the remote sensors of station 121 and 123 (from 20:00 to 21:30). This choice of time period ensures that the changes in the atmosphere during a stationary period can be analysed

Note that there are two sets of plots for station 123. This is due to the fact that, up from 200 m the recirculation zone ends and a new type of flow appears. This flow greatly changes some of the temperature measurements and distorts the plotting of the trend line. It is also helpful to study in isolation the lower heights of measurement which encompass the recirculation zone.

Each figure has a trend line. This line may seem to not accompany the data in the figures. This is due to the fact that there are some points which are out of the selected scale. Since that the sensors measure between every 10 and 30 min, and several heights, a certain difference between values is to be expected. It is unclear whether these correspond to errors in measurement or if they are indeed the actual values at those heights.

**Atmospheric stability towers**

Figures 3.41–3.44 show that the atmosphere was mostly unstable on May 4th during the period of 20:00 to 21:30.



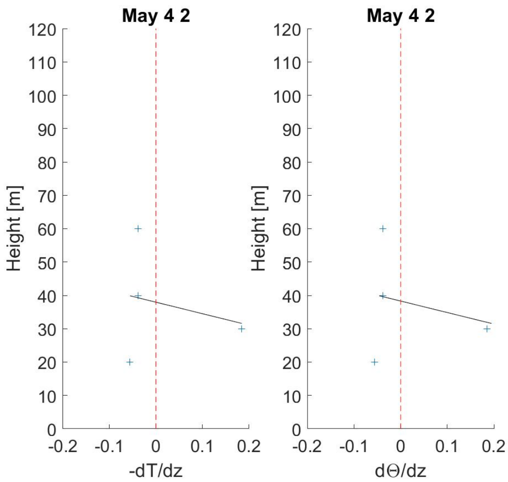

(a) 37/rsw06

(b) 20/tse04

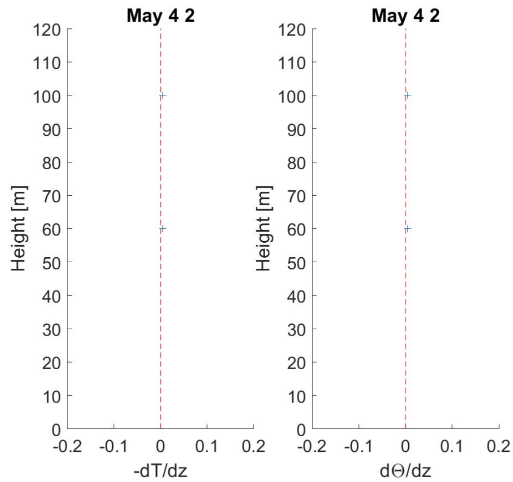
(c) 25/tse09

(d) 29/trSE13

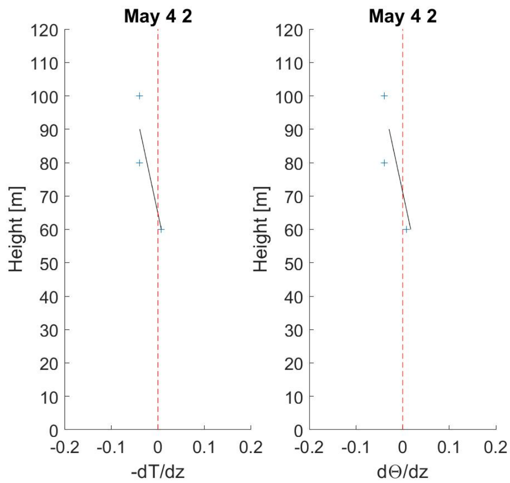
Figure 3.41: May 4 20:00 Temperature and potential temperature gradient all towers with trend line



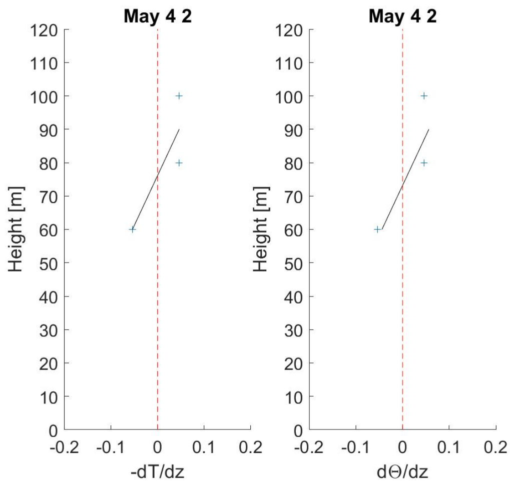

(a) 37/rsw06




(b) 20/tse04

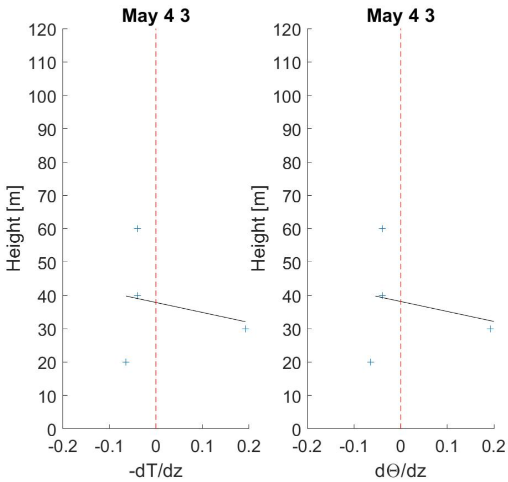



(c) 25/tse09

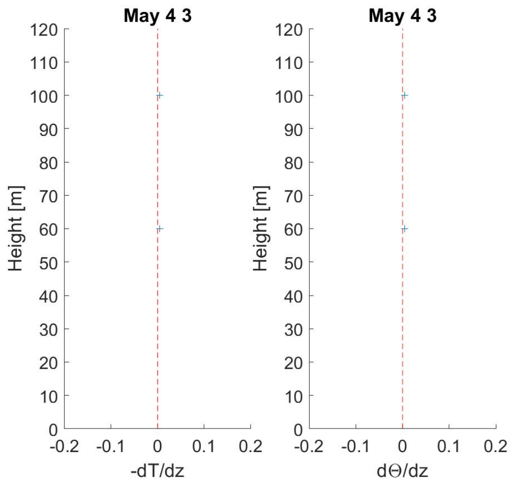



(d) 29/trSE13

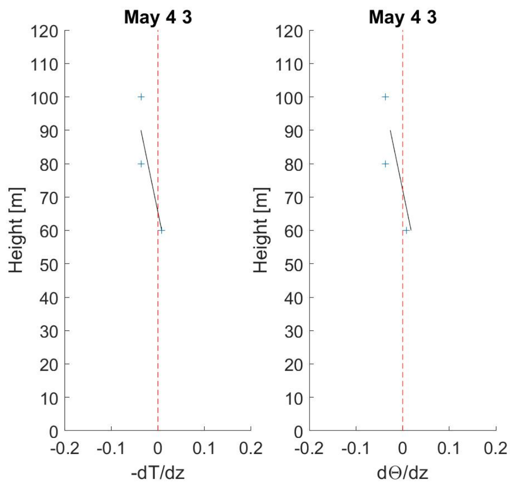
Figure 3.42: May 4 20:30 Temperature and potential temperature gradient all towers with trend line



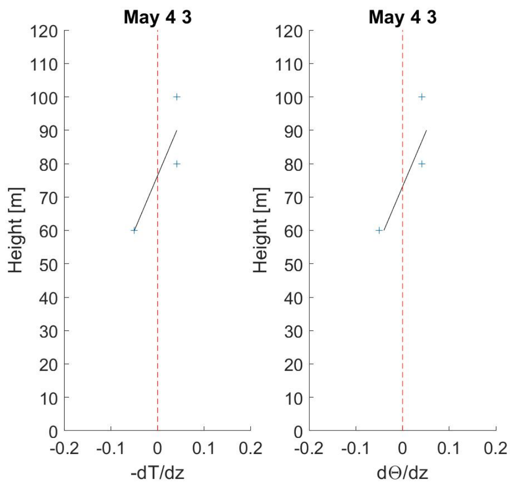

(a) 37/rsw06




(b) 20/tse04

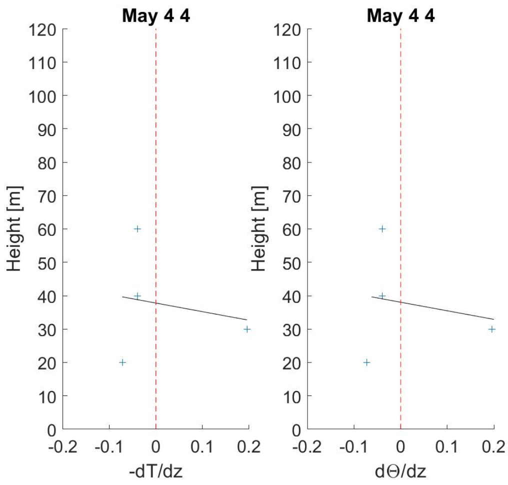



(c) 25/tse09

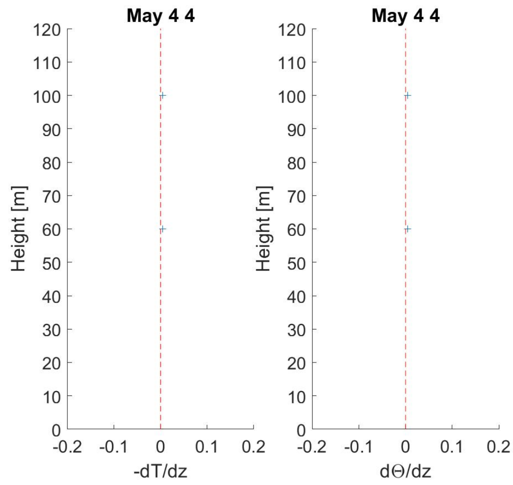



(d) 29/trSE13

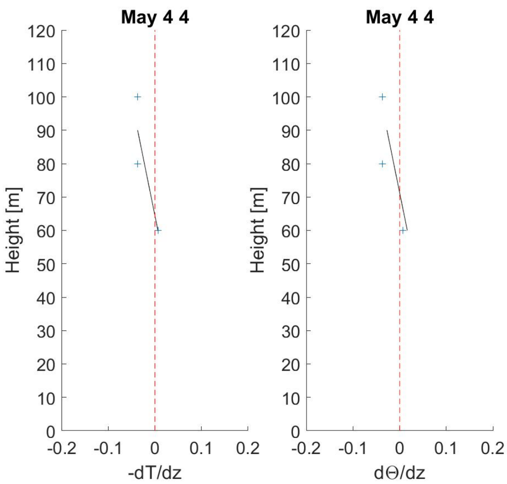
Figure 3.43: May 4 21:00 Temperature and potential temperature gradient all towers with trend line



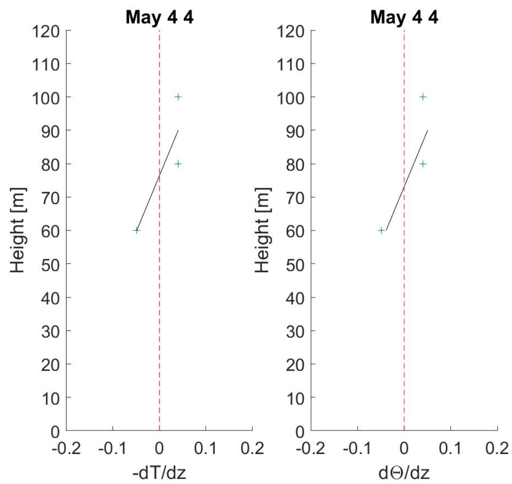

(a) 37/rsw06




(b) 20/tse04




(c) 25/tse09

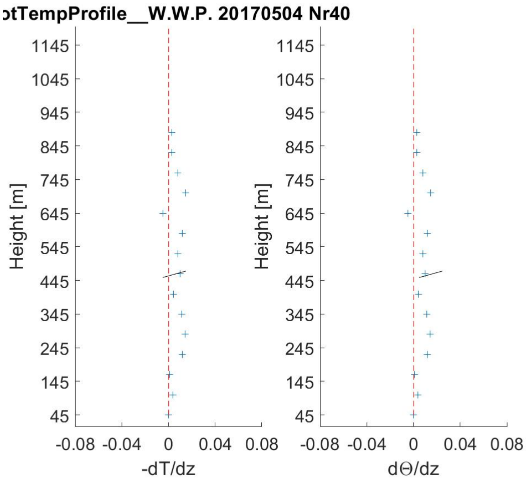



(d) 29/trSE13

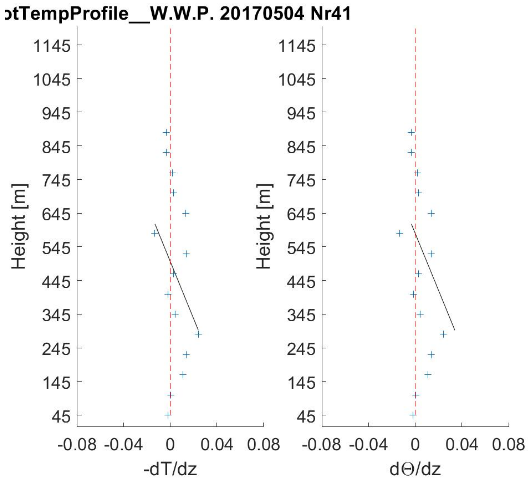
Figure 3.44: May 4 21:30 Temperature and potential temperature gradient all towers with trend line

#### Atmospheric stability remote sensors

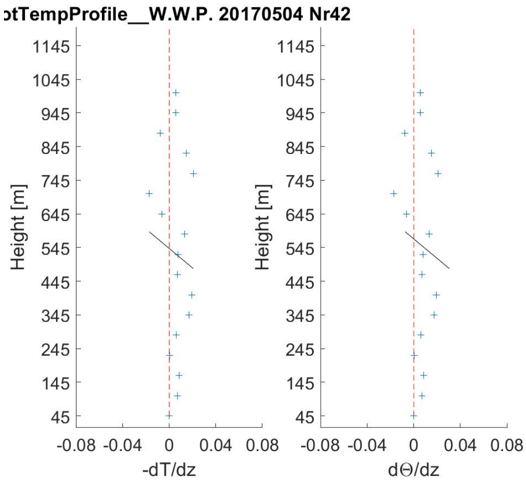
Figures 3.45–3.47 show that the atmosphere was mostly stable during the time period. This conclusion differs from the one in Section 3.7. The differences can be explained by the different positioning of the several instruments (see Section 2.1) and their different heights of measurement (see Section 2.2).



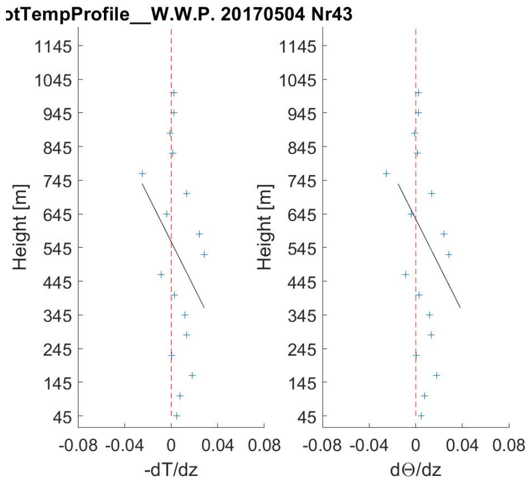

(a) 20:00 station 121




(b) 20:30 station 121

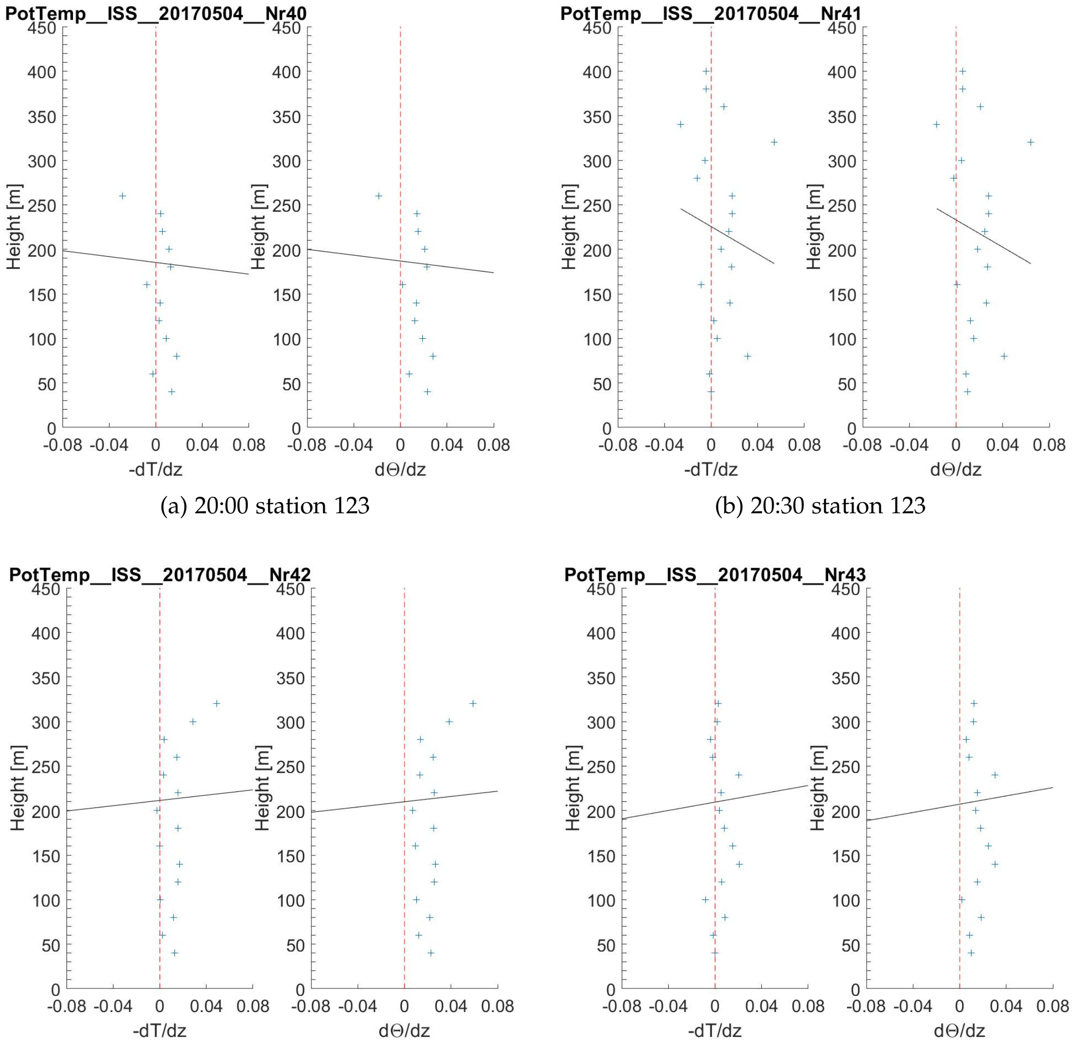



(c) 21:00 station 121




(d) 20:30 station 121

Figure 3.45: May 4, Temperature and potential temperature gradient station 121 with trend line



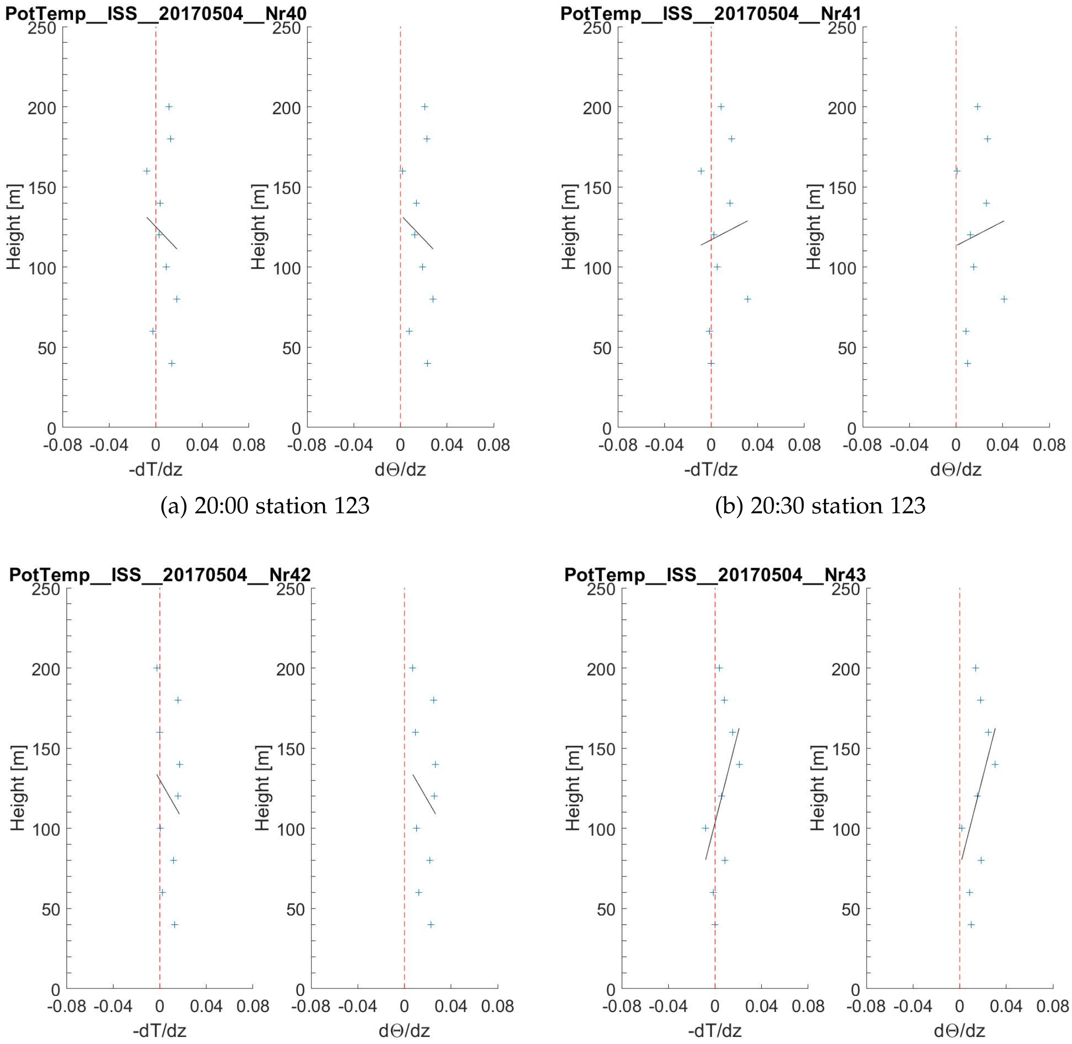

(a) 20:00 station 123

(b) 20:30 station 123

(c) 21:00 station 123

(d) 21:30 station 123

Figure 3.46: May 4 Temperature and potential temperature gradient station 123 (400 m) with trend line




(a) 20:00 station 123

(b) 20:30 station 123

(c) 21:00 station 123

(d) 21:30 station 123

Figure 3.47: May 4 Temperature and potential temperature gradient station 123 (200 m) with trend line

# Chapter 4

# Conclusions and future work

In this chapter the main conclusions (Section 4.1) drawn from this thesis are presented, as well as suggestions for future works (Section 4.2) on this subject.

## 4.1 Conclusions

The following conclusions were deemed the most relevant. They are presented in no particular order:

- The study of only one measuring apparatus, either a tower or a radar or any other, by itself is not enough to give a broad view of the environment surrounding it. This is due to the limitations of the device, its malfunctions and the nature of the phenomena being studied. For instance, a tower is unable to record data for high altitudes, and a wind profiler for near ground heights. Therefore a certain integration of devices is needed.

- While being a normal representation of atmospheric conditions, averages of 10 min have a disadvantage in what concerns spikes and other short duration phenomena. For a better study of such conditions, smaller time periods are needed, such as 5 and 1 min averages, as well as multiple measurements per second.

- The data availability of the towers was greater than that of the sensors.

- Extreme weather conditions, such as thunderstorms, are still very disruptive for the sensors used, therefore more robust apparatus are needed in order to study these phenomena and to give a continuous stream of quality data, regardless of weather conditions.

- It can be observed that, generally, the wind speed increases with height agl, when towers' data are concerned. However, when observing the data from the remote measuring sensors, a more erratic behaviour of wind is seen. Sometimes the speed increases with altitude, sometimes it decreases, sometimes it remains within certain bounds. This is probably due to influences from other wind flows, higher up on the atmosphere, which are unaffected by the ground and the conditions there.

- After reviewing the towers' data it can be seen that the prevailing wind direction is the one expected, NE and WSW, as observed previous measurements on the site. The average wind speed is also in accordance with previous measurements. The recirculation in the valley, with its lower wind speeds and direction parallel to the ridges, could also be observed.
- There were few instances of wind speeds lower than $2\,\mathrm{m\,s^{-1}}$ and almost none higher than $30\,\mathrm{m\,s^{-1}}$, excellent conditions for wind energy.
- Visual observation of time series proved to be a moderately accurate method of encountering stationary time periods.
- A total of 34 stationary periods were encountered and a difference of 2% or 3% between moving averages of 3 points and of 2% between moving averages of 6 points, were found to be the best complement to visual observation of time series in the search for them.
- Most of the stationary periods (23/34) had a wind direction from approximately northeast. Fewer were from the southwest (6/34) and other directions (5/34). This is a rather high number of periods to compare with simulations. It is however unfortunate that there are only 6 such occasions from on of the two main wind directions.
- The average wind speeds of the stationary periods varied between 4.87 and $11.58\,\mathrm{m\,s^{-1}}$. The total average was $7.86\,\mathrm{m\,s^{-1}}$.
- The changes in wind speed usually accompany the ones in wind direction, although the relation between them is unclear. For instance, sometimes when the wind changes due north its speed increases, others it decreases, in the same tower.
- The heterogeneity of measuring instruments gives an additional degree of complexity to data processing. Whenever possible, solutions using the same instruments of a kind should be adopted (for example, always the same type of wind profiler).
- The placement of the instruments proved to be excellent for analysing the flow as it travelled through the site, during any given period of time. However, the fact that the profilers had different characteristics hindered a more complete analysis.
- The atmosphere's stability was characterized for the 4th of May. It was found that at the towers it was unstable, however the data from the remote sensors showed it was stable. Both types of instruments measure at different heights and were placed in different locations. This could account for the difference in $d\theta/dz$ (gradient of potential temperature with height).
- There wasn't a major difference between the wind speeds at night or during the day. For most of the days, the wind speeds were roughly equivalent, however

there were instances when the wind speeds at night were higher than during the day, and vice versa, which was more common

## 4.2 Future work

In order to improve the study of this subject a few suggestions are presented:

- Future work on this topic would benefit from better data sets, or a better way of sorting through the data. This could be achieved with a database with better quality data and a more user friendly environment.
- The MATLAB code used throughout the work can be made faster and more efficient, with experts' help.
- Probably the best option, from the point of view of the user, would be to have a software that allowed for the swift extraction of data sets from a data base and its immediate processing in any number of ways.
- It would be useful to study more towers and measuring instruments, to build upon what has been done here and provide an even better global view of the experiment. This could be complemented with observations offering an even more global view (satellites, weather balloons) in order to provide the best possible combination of observations.
- Another approach would be to study, in greater detail, a single sensor, in order to understand as best as possible the kind of micro scale phenomena that happened in that place (not studied in this work). This can also be useful to better evaluate the quality of the instrument.
- From a different stand point, there could be studies, such as (Martins, 2018), which, by comparing measurements of the same variable at the same time in the same place of several instruments, provide useful insight on the accuracy and reliability of the multiple apparatus used in this kind of experiment.
- One interesting analysis, would be to compare the data and findings of this experiment with that of other experiments in mountainous terrain and look for commonalities between them in order to find new relations or correlations and refine existing ones.
- There could be a similar experiment to study the wind flowing over a mountain and into a valley, but with more wind turbines, in order to gain insight on how the machines influence wind flows.
- More studies concerned with finding a set of criteria, especially ones that can be made into computer algorithms, for evaluating the stationarity of wind speed and direction in time series are needed.

- A study which focuses on the data from the 20 Hz measurements would be most helpful in completing the findings and methods in this study.

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# Appendices

# Appendix A: Matlab scripts

The main MATLAB scripts are presented in this appendix. Several others were used, but these were used more often and to produce most of the figures and tables shown in the document.

## .1 Plot of all 10 minute averages

MATLAB script entitled:
`serie_temporal_de_velocidade_todas_as_componentes_por_10min.m`

Note that this script has been altered after its initial use, in order to calculate the time series of direction and temperature. Those sections are commented (appear after a % sign)

\lstinputlisting[language=Matlab]{C:/Users/ZMVilaca/Desktop/Tese/Matlab/serie_temporal_de

```
% serie temporal para todo o periodo, todos os 10 min

% medicao de todas as componentes partindo de valores medios por
% intervalo de 10 min ao longo de um espaco de tempo a determinar pelo
% ficheiro. Dados retirados ja de um ficheiro com velocidades medias,
% grafico de velocidade por 10 minutos ao longo dos dias


% inputs
M=velocidadehorizontal100mtwr29eliminadosdefeitos; % nome do ficheiro

figures=1;

u=M(:,6);   % vector so com media de U
v=M(:,10);  % vector so com media de V
%  w=M(:,14);  % vector so com media de W

y=sqrt(u.^2+v.^2);  % norma do vector velocidade media

indices = find(abs(y)>30); % eliminar valores de velocidade acima de 30m/s
y(indices) = NaN % idem

um=M(:,8);   % vector so com maximo de U
vm=M(:,12);  % vector so com maximo de V
```

```
am=sqrt(um.^2+vm.^2); % norma do vector velocidade media
indices = find(abs(am)>30); % eliminar valores de velocidade acima de 30m/s
am(indices) = NaN % idem

maximm=max(am(:));
maximm=round(maximm, 2) % arredondar a 2 casas decimais
vvmm=mean(y, 'omitnan'); % calcula a media da velocidade para cada dia
vvmm=round(vvmm, 2) % arredondar a 2 casas decimais
% transforma essa media num vector sempre com o mesmo valor
% e do tamanho de y1m para poder fazer o plot
vm=vvmm.*ones(length(y),1);
desvpadm=std(y,'omitnan');
desvpadm=round(desvpadm, 2) % arredondar a 2 casas decimais

% vector tempo de 0 min ate h horas (de 10 em 10 min) dado
% pelo tamanho de y senao o matlab queixa-se de nao serem do mesmo tamanho
x=1:1:length(y);

%  figure(1)
%  plot(x,y,'.')  % velocidadextempo(em 10 min)

figure(1)
hold on     % para meter os dois plots no mesmo grafico
l1=plot(x,y);  % velocidadextempo(em 10 min)
l2=plot(x,vm, '--');
hold off
% definir o que aparece na legenda do grafico e de que maneira
legend([l2],['avg speed [m/s]=' num2str(vvmm),' ',...
    'max[m/s]=' num2str(maximm),' ','std=' num2str(desvpadm)]);
% definir tamnho de letra e legenda transparente
legend('boxoff','FontSize',10,'NumColumns',1);

title('Time Series averages of 10 min 29/trSE 13 at 100m');
% definir escala em horas
set(gca,'XTick',[0:288:6624],'XTickLabel',...
                                [1:2:47],'XAxisLocation','bottom');
set(gca, 'box', 'on');
ylim([0 30]);
ylabel('Horizontal Wind Speed [m/s]');
xlabel('Days of the experiment');

for f = 1:numel(figures)
      fig = figures(f);

      % Output the figure

      filename = sprintf('29trSE_13AllDays10minTimeSerie100m.pdf',f);
      print( fig, '-dpdf', filename );
end

for f = 1:numel(figures)
      fig = figures(f);

      % Output the figure

      filename = sprintf('29trSE_13AllDays10minTimeSeries100m.jpg',f);
      print( fig, '-djpeg', filename );
end
```

## .2 Daily time series with wind speed, direction and temperature

MATLAB script entitled:
`serie_temporal_por_dia_com_direccao_e_T.m`

Note that this script has been altered after its initial use, in order to moving averages. Those sections appear together with the original code.

\lstinputlisting[language=Matlab]{C:/Users/ZMVilaca/Desktop/Tese/Matlab/serie_temporal_po

```
%serie temporal por dia, todos os dias, medias de 10 min, juntamente com a
%direccao e a temperatura


S=perdigaonewa20170501to20170615uvwtwr3760melimiadosdefeitos; %ficheiro das
%velocidades
D=perdigaonewa20170501to20170615trw3760mdirecaoeliminadosdefeitos %ficheiro
%das direccoes
T=Temperatura3760meliminadosdefeitos; %ficheiro da temperatura

%%----------torre 37------------------
% velocidade
S = insertrows(S,NaN(30,17),598); %dia 5
S = insertrows(S,NaN(92,17),1412); %dia 10 e 11
S = insertrows(S,NaN(120,17),1523); %dia 11 e 12
S = insertrows(S,NaN(4,17),1646); %dia 12
S = insertrows(S,NaN(73,17),3440); %dia 24 e 25
S = insertrows(S,NaN(64,17),4177); %dia 30

% direccao
D = insertrows(D,NaN(30,9),598); %dia 5
D = insertrows(D,NaN(92,9),1412); %dia 10 e 11
D = insertrows(D,NaN(120,9),1523); %dia 11 e 12
D = insertrows(D,NaN(4,9),1646); %dia 12
D = insertrows(D,NaN(73,9),3440); %dia 24 e 25
D = insertrows(D,NaN(64,9),4177); %dia 30

% temperatura
T= insertrows(T,NaN(30,9),598); %dia 5
T = insertrows(T,NaN(92,9),1412); %dia 10 e 11
T = insertrows(T,NaN(120,9),1523); %dia 11 e 12
T = insertrows(T,NaN(4,9),1646); %dia 12
T = insertrows(T,NaN(73,9),3440); %dia 24 e 25
T = insertrows(T,NaN(64,9),4177); %dia 30



% u=S(:,6);   %vector so com media de U
% v=S(:,10);  %vector so com media de V
% y1m=sqrt(u.^2+v.^2); %norma do vector velocidade media
%
%
%  um=S(:,8);   %vector so com maximo de U
%  vm=S(:,12);  %vector so com maximo de V
%  umin=S(:,7);   %vector so com minimo de U necessario, porque as vezes
%aparecem valores negativos e o minimo passa a ser o maximo
%  vmin=S(:,11);   %vector so com minimo de V
```

```
% %
%  am=sqrt(um.^2+vm.^2);  %norma do vector velocidade maxima
%   indices = find(abs(am)>30); %eliminar valores de velocidade acima de
%30m/s
%  am(indices) = NaN %idem
% %
%  amin=sqrt(umin.^2+vmin.^2);  %norma do vector velocidade minima
%  indices = find(abs(amin)>30); %eliminar valores de velocidade acima de
%30m/s
% amin(indices) = NaN %idem
%
%
% v=[y1m(:) amin(:) am(:)];
%
%

d=46; %dias a avaliar de 1 a 46, ver comentarios a seguir para resto
%de explicacao
figures=[1:1:d];

%-----------------------maio--------------------------

for a=1:1:d-15 %dias de maio a avaliar
dii=a; %dia inicial que se quer estudar de 1 a 45. 1/5/17 e dia 1, 2/5/17
%e dia 2 e sucessivamente ate 15/6/17 dia 44
dff=a; %dia final que se quer estudar de 1 a 45. 1/5/17 e dia 1, 2/5/17
%e dia 2 e sucessivamente ate 15/6/17 dia 44


p=(dii -1)*144+1:1:(dff+1)*144-144; %vector que da o intervalo em grupos
%de 10 min que se pretende, de acordo com os dias que se escolheram
p=p'; %transpor esse vector para o transformar em vector coluna

u=S(p,9);   %vector so com media de U
v=S(p,13);  %vector so com media de V
y1m=sqrt(u.^2+v.^2);  %norma do vector velocidade media
y2m=D(p,9);  %vector com as direccoes
y3m=T(p,9); %vector com as temperaturas
indices = find(abs(y1m)>5); %eliminar valores de velocidade acima de 30m/s
y1m(indices) = NaN %idem
indices = find(abs(y3m)>5); %eliminar valores de temperatura acima de 55  C
y3m(indices) = NaN %idem
xm=1:1:length(y1m);  %vector tempo de 0 min ate h horas (de 10 em 10 min)
%dado pelo tamanho de y senao o matlab queixa-se de nao serem do mesmo
%tamanho
indices = find(abs(y2m)>15); %eliminar valores de temperatura acima de 55 C
y2m(indices) = NaN %idem


vmm=movmean(y1m,3); %media movel velocidade
dmm=movmean(y2m,3); %media movel direccao
tmm=movmean(y3m,3); %media movel temperatura

% um=S(p,8);   %vector so com maximo de U
% vm=S(p,12);  %vector so com maximo de V
% umin=S(p,7);   %vector so com minimo de U necessario, porque as vezes
%aparecem valores negativos e o minimo passa a ser o maximo
% vmin=S(p,11);   %vector so com minimo de V
```

```
%
% am=sqrt(um.^2+vm.^2);  %norma do vector velocidade maxima
% indices = find(abs(am)>30); %eliminar valores de velocidade acima de
%30m/s
% am(indices) = NaN %idem
%
% amin=sqrt(umin.^2+vmin.^2);  %norma do vector velocidade minima
% indices = find(abs(amin)>30); %eliminar valores de velocidade acima de
%30m/s
% amin(indices) = NaN %idem
%
% velmax=[am(:), amin(:)]; %matriz com a velocidade minima e maxima
%
% maximm=max(max(velmax(:)));  %encontra o valor maximo da velocidade para
%cada dia
% maximm=round(maximm, 2) %arredondar a 2 casas decimais
% vvmm=mean(y1m, 'omitnan');  %calcula a media da velocidade para cada dia
% vvmm=round(vvmm, 2) %arredondar a 2 casas decimais
% vm=vvmm.*ones(length(y3m),1);  %transforma essa media num vector sempre
%com o mesmo valor e do tamanho de y1m para poder fazer o plot
% desvpadm=std(y1m,'omitnan');
% desvpadm=round(desvpadm, 2) %arredondar a 2 casas decimais

A{d} =  sprintf('May %d',a); %nomear as figuras de 1 a 31 de maio

% fazer grafico usando funcao plotyyy para poder ter 3 funcoes com 3 eixos
 %y no mesmo grafico

 %legenda dos eixos
 ylabels{1}='Windspeed  (Blue)';  %legenda velocidade eixo ax1
 ylabels{2}='Direction  (Cyan)';  %legenda direccao eixo ax2
 ylabels{3}='Temperature  (Red)';  %temperatura eixo ax3
 [ax,hlines] = plotyyy(xm,vmm,xm,dmm,xm,tmm,ylabels);  %fazer o grafico
 title(A{d}); %da o titulo de acordo com os dias
 hold(ax(1), 'on');
% l1=plot(ax(1),vm, '--');%meter linha horizontal de velocidade media no
%eixo das veleocidades
% legend([l1],['daily avg speed [m/s]=' num2str(vvmm),' ','max[m/s]='
%num2str(maximm),' ','std=' num2str(desvpadm)]);
%definir o que aparece na legenda do grafico e de que maneira
% legend('boxoff','FontSize',10);  %definir tamnho de letra e legenda
%transparente
 hold(ax(1), 'off');

 set(ax(1),'XTick',[0:12:144],'XTickLabel',[0:2:24],'XAxisLocation',...
     'bottom');  %definir escala em horas
 set(ax(1),'YLim',[0 5],'ycolor','k');  %escala das velocidades limites
%e cor dos eixos
 set(hlines(1),'LineWidth',2); %linha da velocidade mais grossa
 set(hlines(2),'Color','c'); %linha da direccao a azul ciano
 set(ax(2),'YLim',[0 15],'ycolor','k'); %escala das direccoes limites e
%cor dos eixos
 set(ax(3),'YLim',[0 5],'ycolor','k'); %escala das temperaturas limites e
%cor dos eixos
 set(ax(1),'Box','on'); %definir eixo do x superior
 set(ax(1),'YTick',[0:1:5]); %escala de velocidades
 set(ax(2),'YTick',[0:1:15]); %escala de direcoes
 set(ax(3),'YTick',[0:1:5]); %escala de temperaturas
```

```
xlabel(ax(1),'UTC'); %legenda no eixo x


end


%%----------------------junho----------------------


for a=d-14:1:d %dias de junho a avaliar
dii=a; %dia inicial que se quer estudar de 1 a 45. 1/5/17 e dia 1, 2/5/17 e
%dia 2 e sucessivamente ate 15/6/17 dia 44
dff=a; %dia final que se quer estudar de 1 a 45. 1/5/17 e dia 1, 2/5/17
%e dia 2 e sucessivamente ate 15/6/17 dia 44


p=(dii-1)*144+1:1:(dff+1)*144-144; %vector que da o intervalo em grupos de
%10 min que se pretende, de acordo com os dias que se escolheram
p=p'; %transpor esse vector para o transformar em vector coluna

u=S(p,9); %vector so com media de U
v=S(p,13); %vector so com media de V
y1j=sqrt(u.^2+v.^2); %norma do vector velocidade media
y2j=D(p,9); %vector com as direccoes
y3j=T(p,9); %vector com as temperaturas
indices = find(abs(y1j)>5); %eliminar valores de velocidade acima de 30m/s
y1j(indices) = NaN %idem
indices = find(abs(y3j)>5); %eliminar valores de temperatura acima de 55 C
y3j(indices) = NaN %idem
xj=1:1:length(y1j); %vector tempo de 0 min ate h horas (de 10 em 10 min)
%dado pelo tamanho de y senao o matlab queixa-se de nao serem do mesmo
%tamanho
indices = find(abs(y2j)>15); %eliminar valores de temperatura acima de 55 C
y2j(indices) = NaN %idem
vmj=movmean(y1j,3); %media movel velocidade
dmj=movmean(y2j,3); %media movel direccao
tmj=movmean(y3j,3); %media movel temperatura



% um=S(p,8); %vector so com maximo de U
% vm=S(p,12); %vector so com maximo de V
% umin=S(p,7); %vector so com minimo de U necessario, porque as vezes
%aparecem valores negativos e o minimo passa a ser o maximo
% vmin=S(p,11); %vector so com minimo de V
%
% am=sqrt(um.^2+vm.^2); %norma do vector velocidade maxima
% indices = find(abs(am)>30); %eliminar valores de velocidade acima de30m/s
% am(indices) = NaN %idem
%
% amin=sqrt(umin.^2+vmin.^2); %norma do vector velocidade minima
% indices = find(abs(amin)>30); %eliminar valores de velocidade acima de
%30m/s
% amin(indices) = NaN %idem
%
% velmax=[am(:), amin(:)]; %matriz com a velocidade minima e maxima
%
% maximj=max(max(velmax(:))); %valor maximo do periodo
```

```
% maximj=round(maximj, 2) %arredondar a 2 casas decimais
% vvmj=mean(y1j, 'omitnan'); %calcula a media da velocidade para cada dia
% vvmj=round(vvmj, 2) %arredondar a 2 casas decimais
% vj=vvmj.*ones(length(y3j),1); %transforma essa media num vector sempre
%com o mesmo valor e do tamanho de y1m para poder fazer o plot
% desvpadj=std(y1j,'omitnan'); %calcaula o desvio padrao
% desvpadj=round(desvpadj, 2) %arredondar a 2 casas decimais


A{d} = sprintf('June %d',a-31); %nomear as figuras de 1 a 15 de junho

 %fazer grafico usando funcao plotyyy para poder ter 3 funcoes com 3 eixos
 %y no mesmo grafico

 %legenda dos eixos
 ylabels{1}='Windspeed (Blue)'; %legenda velocidade eixo ax1
 ylabels{2}='Direction (Cyan)'; %legenda direccao eixo ax2
 ylabels{3}='Temperature (Red)'; %temperatura eixo ax3

 [ax,hlines] = plotyyy(xj,vmj,xj,dmj,xj,tmj,ylabels); %fazer o grafico
 title(A{d}); %da o titulo de acordo com os dias
 hold(ax(1), 'on');
% l1=plot(ax(1),vj, '--');%meter linha horizontal de velocidade media no
%eixo das veleocidades
% legend([l1],['daily average speed [m/s]=' num2str(vvmj),' ','max[m/s]='
%num2str(maximj),' ','std=' num2str(desvpadj)]); %definir o que aparece na
%legenda do grafico e de que maneira
% legend('boxoff','FontSize',10); %definir tamnho de letra e legenda
%transparente
 hold(ax(1), 'off');

 set(ax(1),'XTick',[0:12:144],'XTickLabel',[0:2:24],'XAxisLocation',...
     'bottom'); %definir escala em horas
 set(ax(1),'YLim',[0 5],'ycolor','k'); %escala das velocidades limites
%e cor dos eixos
 set(hlines(1),'LineWidth',2); %linha da velocidade mais grossa
 set(hlines(2),'Color','c'); %linha da direccao mais grossa
 set(ax(2),'YLim',[0 15],'ycolor','k'); %escala das direccoes limites e
%cor dos eixos
 set(ax(3),'YLim',[0 5],'ycolor','k'); %escala das temperaturas limites e
%cor dos eixos
 set(ax(1),'Box','on'); %definir eixo do x superior
 set(ax(1),'YTick',[0:1:5]); %escala de velocidades
 set(ax(2),'YTick',[0:1:15]); %escala de direcoes
 set(ax(3),'YTick',[0:1:5]); %escala de temperaturas
 xlabel(ax(1),'UTC'); %legenda no eixo x

 end



% for f = 1:numel(figures)
%        fig = figures(f);
%
%        %Output the figure
%
%        filename = sprintf('37MedMov3TimeSeries%02d.pdf',f);
%        print( fig, '-dpdf', filename );
```

```
% end

for f = 1:numel(figures)
    fig = figures(f);

    %Output the figure

    filename = sprintf('37MedMov3StdDevTimeSeries%02d.jpg',f);
    print( fig, '-djpeg', filename );
end
```

## .3 Daily wind roses

MATLAB script entitled:
`rosa_das_velocidades_com_valores_acima_de_um_valor_indicado.m`

\lstinputlisting[language=Matlab]{C:/Users/ZMVilaca/Desktop/Tese/Matlab/rosa_das_velocida

```
%rosa das velocidades com valores acima de um valor indicado, usando a
%funcao Windrose. Se se pedir para eliminar valores que nao existem nos
%dados da erro na windrose, atencao a isso

%da para usar um qualquer intervalo de dias, desde que os ficheiros estejam
%devidamente preparados para isso

S=perdigaonewa20170501to20170615uvwa80mtwr25sem530; %ficheiro das
%velocidades
D=direcao80mtwr25sem530; %ficheiro das direccoe


d=46; %dias a avaliar de 1 a 46, ver comentarios a seguir para resto de
%explicacao
figures=[1:1:d];


%-------------Maio---------------

for a=1:1:d-15 %dias de maio a avaliar
dii=a; %dia inicial que se quer estudar de 1 a 45. 1/5/17 e dia 1, 2/5/17
%e dia 2 e sucessivamente ate 15/6/17 dia 44
dff=a; %dia final que se quer estudar de 1 a 45. 1/5/17 e dia 1, 2/5/17
%e dia 2 e sucessivamente ate 15/6/17 dia 44

%como os ficheiros tem o dia 4 e o 29 repetidos para colmatar a falta do
%dia 5 e 30 e preciso ter atencao a isso nas imagens finais

p=(dii-1)*144+1:1:(dff+1)*144-144; %vector que da o intervalo em grupos
%de 10 min que se pretende, de acordo com os dias que se escolheram
p=p'; %transpor esse vector para o transformar em vector coluna

u=S(p,6); %componente u
v=S(p,10); %componente v
spd=sqrt(u.^2+v.^2); %norma da velocidade

indices = find(abs(spd)>30); %eliminar valores de velocidade abaixo de
%um valor especificado
spd(indices) = NaN %idem
um=S(:,8); %vector so com maximo de U
vm=S(:,12); %vector so com maximo de V

am=sqrt(um.^2+vm.^2); %norma do vector velocidade media
indices = find(abs(am)>30); %eliminar valores de velocidade acima de 30m/s
am(indices) = NaN %idem

maximm=max(am(:));
maximm=round(maximm, 2) %arredondar a 2 casas decimais
vvmm=mean(spd, 'omitnan'); %calcula a media da velocidade para cada dia
vvmm=round(vvmm, 2) %arredondar a 2 casas decimai
```

```
desvpadm=std(spd,'omitnan');
desvpadm=round(desvpadm, 2) %arredondar a 2 casas decimais



dir=D(p,6); %vector com a direccao do vento
Se_igual_a_1_nao_ha_velocidade_0=all(spd) %teste logico para ver alguma
%velocidade e 0. Se B=1 nao ha spd=0, se B for 0 e porque ha


% a partir daqui sao as coisas da Windrose, como chamar a funcao e que
% grafico fazer

 A{d} =  sprintf('May %d',a); %nomear as figuras de 1 a 31 de maio

    Options = {'anglenorth',0,'angleeast',90,'labels',{'N (0)',...
        'S (180)','E (90)','W (270)'}, 'freqlabelangle',45};
[figure_handle,count,speeds,directions,Table] = WindRose(dir,spd,...
    'nDirections',36,'LegendType',0,'height',512,'width',700,...
    'vWinds',[0 0.28 2 4 6 8 10 12 14 16],'Min_Radius',0,'TitleString'...
    ,A,'FreqLabelAngle',60); %definir figura sem um buraco no meio e
%com as frequencias das ocorrencias na figura
%WindRose(dir,spd,'vWinds',[0 3 6 9 12 15]); %definir intervalos de
%velocidade que quero que aparecam, tendo em conta que a velocidade
%horizontal maxima e cerca de 17m/s
%'height',256,'width',512 %definir dimensoes da figura em pixeis
legend(['avg speed [m/s]=' num2str(vvmm),' ','max[m/s]=' num2str(maximm),..
   %' ','std=' num2str(desvpadm)],'Location', 'southwest'); %definir o
   %que aparece na legenda do grafico e de que maneira
% legend('boxoff'); %legenda transparente
end

%--------------------Junho---------------------------

for a=d-14:1:d %dias de junho a avaliar
dii=a; %dia inicial que se quer estudar de 1 a 45. 1/5/17 e dia 1, 2/5/17
%e dia 2 e sucessivamente ate 15/6/17 dia 44
dff=a; %dia final que se quer estudar de 1 a 45. 1/5/17 e dia 1, 2/5/17
%e dia 2 e sucessivamente ate 15/6/17 dia 44

%%NOTA: O dia 5/5 e 30/5 foram retirados, portanto o dia 6/5 corresponde ao
%%dia 5 do script e o dia 31 ao dia 29

p=(dii-1)*144+1:1:(dff+1)*144-144; %vector que da o intervalo em grupos
%de 10 min que se pretende, de acordo com os dias que se escolheram
p=p'; %transpor esse vector para o transformar em vector coluna


u=S(p,6); %componente u
v=S(p,10); %componente v
spd=sqrt(u.^2+v.^2); %norma da velocidade

indices = find(abs(spd)>30); %eliminar valores de velocidade abaixo de
%um valor especificado
spd(indices) = NaN %idem

um=S(:,8);   %vector so com maximo de U
vm=S(:,12);  %vector so com maximo de V
```

```
am=sqrt(um.^2+vm.^2);  %norma do vector velocidade media
indices = find(abs(am)>30); %eliminar valores de velocidade acima de 30m/s
am(indices) = NaN %idem

maximj=max(am(:));
maximj=round(maximj, 2) %arredondar a 2 casas decimais
vvmj=mean(spd, 'omitnan');  %calcula a media da velocidade para cada dia
vvmj=round(vvmj, 2) %arredondar a 2 casas decimai
desvpadj=std(spd,'omitnan');
desvpadj=round(desvpadj, 2) %arredondar a 2 casas decimais


dir=D(p,6); %vector com a direccao do vento
Se_igual_a_1_nao_ha_velocidade_0=all(spd)  %teste logico para ver alguma
%velocidade e 0. Se B=1 nao ha spd=0, se B for 0 e porque ha


% a partir daqui sao as coisas da Windrose, como chamar a funcao e que
% grafico fazer


A{d} =  sprintf('June %d',a-31);  %nomear as figuras de 1 a 15 de junho

    Options = {'anglenorth',0,'angleeast',90,'labels',{'N (0)',...
        'S (180)','E (90)','W (270)'}, 'freqlabelangle',45};
[figure_handle,count,speeds,directions,Table] = WindRose(dir,spd,...
'nDirections',36,'LegendType',0,'height',512,'width',700, 'vWinds'...
,[0 0.28 2 4 6 8 10 12 14 16],'Min_Radius',0,'TitleString',A,...
'FreqLabelAngle',60);  %definir figura sem um buraco no meio e com as
%frequencias das ocorrencias na figura

legend(['avg speed [m/s]=' num2str(vvmj),' ','max[m/s]=' num2str(maximj),..
' ','std=' num2str(desvpadj)],'Location', 'southwest');
%definir o que aparece na legenda do grafico e de que maneira

% WindRose(dir,spd,'vWinds',[0 3 6 9 12 15]);  %definir intervalos de
%velocidade que quero que aparecam, tendo em conta que a velocidade
%horizontal maxima e cerca de 17m/s
% 'height',256,'width',512  %definir dimensoes da figura em pixeis
end

%  ciclo para gravar todas as imagens no formato de ficheiro que quiser
%em ficheiros separados, um por
% imagem

% for f = 1:numel(figures)
%       fig = figures(f);
% %
%       % Output the figure
%
%       filename = sprintf('37riSW_06IOP%02d.jpg',f);
%       print( fig, '-djpeg', filename );
% end
%
% for f = 1:numel(figures)
%       fig = figures(f);
% %
```

```
%          % Output the figure
%
%          filename = sprintf('37riSW_06IOP%02d.pdf',f);
%          print( fig , '-dpdf', filename );
% end
%
```

## .4 Plot of velocity profiles and wind direction

MATLAB script entitled:

`lerNetCdfNCAS.m`

`\lstinputlisting[language=Matlab]{C:/Users/ZMVilaca/Desktop/Tese/Matlab/lerNetCdfNCAS.m}`

```
%Para dados do radar NCAS le o ficheiro netcdf que quiser e faz o perfil de velocidades para a
%variavel data

%%NOTAS::
%e preciso andar a alterar as datas nos caminho do ficheiro em filename e no nome2 senao da asn
%e preciso andar a comentar e desocmentar coisas no meio de acordo com o que se quer:
% se e velcoidade se temperatura, se de 15 em 15 se de 1 em 1 etc


clear all %limpa o workspace mal comeca a correr o script, util para evitar asneiras

%-------------ler netcdf------------------

nome2=' radar__alvaiade__20170501__Nr ';
nome3='2017_05_01';
%%::::::::::::NCAS profiler:::::::::::::::::
 %%-----------------velocidade e direccao--------------------
%nome='man-radar-1290mhz_alvaiade_20170501_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170502_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170503_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170504_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170505_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170506_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170507_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170508_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170509_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170510_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170511_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170512_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170513_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170514_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170515_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170516_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170517_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170518_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170519_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170520_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170521_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170522_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170523_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170524_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170525_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170526_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170527_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170528_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170529_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170530_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170531_high-range-mode-15min'
```

```
%nome='man-radar-1290mhz_alvaiade_20170601_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170602_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170603_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170604_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170605_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170606_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170607_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170608_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170609_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170610_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170611_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170612_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170613_high-range-mode-15min'
%nome='man-radar-1290mhz_alvaiade_20170614_high-range-mode-15min'
nome='man-radar-1290mhz_alvaiade_20170615_high-range-mode-15min'



% %---------------temperatura com altura-----------------
% file_name = strcat('C:\Users\ZMVilaca\Desktop\tese\ucar datasetswestwind\nima.20170501.nc\',n
% var_name = 'tvc'; %temperatura
% var_name2 = 'heights'; %altura
% var_name3 = 'time'; %tempo
% group_name = '/grid2/';
% tmp = var_name; % or tmp = group_name

%----------velocidade e direccao com altura-------------
file_name = strcat('C:\Users\ZMVilaca\Desktop\tese\NCAS_profiler\ncdf\',nome,'.nc');
var_name = 'wind_speed'; %velocidade
var_name2 = 'altitude'; %altura
var_name3 = 'wind_from_direction'; %direccao
group_name = '/grid2/';
tmp = var_name; % or tmp = group_name

% Display global information about a netcdf file
ncdisp(file_name);
% About a variable or a group
ncdisp(file_name, tmp);
% In the specified format 'full' or 'min'
ncdisp(file_name, tmp, 'min');


% Get information about a netcdf file
info = ncinfo(file_name)
% About a variable
var_info = ncinfo(file_name, var_name)
% About a group
%gr_info = ncinfo(file_name, group_name)


% Read data from a vraiable of a netcdf file
data = ncread(file_name, var_name); %velocidade*tempo
data2 = ncread(file_name, var_name2); %altura*tempo
data3 = ncread(file_name, var_name3); %direccao*tempo
% Or
% data = ncread(file_name, var_name, start, count, stride)
```

```
% Read attribute
% attr = ncreadatt(file_name, '/', 'creation_date')
% var_attr = ncreadatt(file_name, var_name, 'add_offset')
% %gr_attr = ncreadatt(file_name, group_name, 'description')


%%---------------contar picos de velocidade-------------------

indices = find(abs(data)>30); %eliminar valores de velocidade acima de 30m/s



%%--------contar nans para ver a disponibilidade dos dados-------------
%
% data=data(1:35,:); %elimina todas as linhas de NaNs para as alturas nao existentes
% data3=data3(1:35,:);
% data2=data2(1:35,:);
%
% nansVEL=find(isnan(data));
% taVEL=length(nansVEL);
% TVEL=size(data);
% TTVEL=TVEL(1).*TVEL(2);
% dispVEL=100-(length(nansVEL)/3360)*100;
% 3360 e 35*96, e a quantidade de observacoes que deveria de aparecer nos
% dados. se der numeros estupidos e porque a matriz original nao tinha 48*48
% nansDIR=find(isnan(data3));
% taDIR=length(nansDIR);
% TDIR=size(data3);
% TTDIR=TDIR(1).*TDIR(2);
% dispDIR=100-(length(nansDIR)/3360)*100;
%

% %%---------------box and whiskers-------------------------------------
%
% %media de tempo para juntar todas as colunas e fazer uma media diaria
%
% vm = reshape(data, size(data,1), 96, [])      % Reshape para a velocidade
% vm = squeeze(mean(vm,2,'omitnan'))            % Desired Result
%
% vm2 = reshape(data2, size(data2,1), 96, [])      % Reshape para a direccao
% vm2 = squeeze(mean(vm2,2,'omitnan'))            % Desired Result
%
%  x=vm; %retirar so a coluna da velocidade/temperatura para cada tempo
%  y=vm2; %retirar so a coluna de alturas para cada tempo




%%------------------media e maxima---------------------
%
% x=data(5,:); %retirar so a linha das velocidades a 979m
%
% velmedia=mean(x,'omitnan');
%
% velmax=max(x);
```

```
%———————————fazer perfis ————————————————

%ha coisas que estao comentadas que sao linhas de codigo para correr com
%coisas diferentes, tipo velocidade ou temperatura. e preciso comentar e
%descomentar as partes relevantes

%   c=find(all(isnan(data),1));  %encontrar indices das colunas que so tem
%   nans na matriz da velocidade
%   data(:,[c(:)])=9999; %substituir por 999 todos os valores das colunas
%   que so tem NaNs que assim nao aparecem no grafico e os  numeros da
%   imagem batem certo com os tempos
%   data2(:,[c(:)])=99999; %fazer o mesmo nas colunas correspondentes
%              na matriz das alturas
%   data3(:,[c(:)])=9999; %fazer o mesmo nas colunas correspondentes
%             na matriz das direccoes
%
%
%  ciclo para fazer plot por coluna para cada coluna (tempo)
%
% media de tempo, de 2 em 2 colunas, para o ficheiro de 15 min dar graficos
% de meia hora
%
% data = reshape(data, size(data,1), 2, [])      % Reshape para a velocidade
% data = squeeze(mean(data,2,'omitnan'))         % Desired Result
%
% data3 = reshape(data3, size(data3,1), 2, [])      % Reshape para a direccao
% data3 = squeeze(mean(data3,2,'omitnan'))         % Desired Result
%
%
% media de tempo, de 30 em 30 colunas, para o ficheiro de 1 min dar graficos
% de meia hora
%
% data = reshape(data, size(data,1), 30, [])      % Reshape para a velocidade
% data = squeeze(mean(data,2,'omitnan'))         % Desired Result
%
% data3 = reshape(data3, size(data3,1), 30, [])      % Reshape para a direccao
% data3 = squeeze(mean(data3,2,'omitnan'))         % Desired Result

%
% for i=1:48  %definir numero de iteracoes do ciclo como o comprimento da matriz data (numero d
%  x=data(:,i); %retirar so a coluna da velocidade/temperatura para cada tempo
%  y=data2(:,i); %retirar so a coluna de alturas para cada tempo
%  z=data3(:,i); %retirar so a coluna de direccoes para cada tempo
%  %z=data3(i,:) %retira cada valor de tempo para usar no titulo das imagens e saber a que segu
% %hms = fix(mod(z, [0, 3600]) ./ [3600, 60]) %converter de segundos para horas
% % z=round(z,1); %arredondar a 1a casa decimal. o fomrat long e para nao aparecer e+0002 e cen
% % sprintf('%f', z);
%
% t=i*30;   %tempo em min para meter na legenda da figura
%
% hms=t/60;
%
% z(isnan(x)) = []%eliminar Nans de x nos valores correspondentes de z
% y(isnan(x)) = []%eliminar Nans de x nos valores correspondentes de y
% x(isnan(x)) = [] %remover nans para a funcao poder ser ajustada
%
%
```

```
%
% %definir vectores todos do mesmo tamanho, vao ficar do tamanho do maior e o
% %resto fica preenchido com [] senao nao ajusta a funcao
% maxLength = max([length(x),length(y),length(z)])
% x(length(x)+1:maxLength) = [];
% y(length(y)+1:maxLength) = [];
% z(length(z)+1:maxLength) = []; %retirar comentario quando houver direccao, comentar quando h
%
%
% % ciclo para calcular o shear facto medio
% for j=1:length(x)-1 %ATENcaO: VAI FALTAR O ULTIMO VALOR PORQUE O MATLAB QUEIXA-SE QUE "INDEX
%
%    alfa(j)=(log(x(j)/x(j+1))/log(y(j)/y(j+1))); %shear factor medio de todos os valores
%
%    alfa=round(alfa,3); %arredondar a 3a casa decimal
% yy=1:j; %vector y para poder fazer plot de alfa
% end
% % fazer a figura
% figure(i)
%
% %comentar quando e para fazer so uma figura por dia com todos os perfis no
% %mesmo grafico. se e para fazer 48 descomentar
% subplot(2,2,[1 3]); %fazer subplot com velocidade
% %f = fit(x,y,'exp1'); %plot exponencial
% plot(x,y,'.'); %plot com ajustamento exponencial velocidade*altura
% %legend('Location','northeast'); %legenda da imagem
% %text(17, 4000,['avg \alpha=' num2str(alfa)]); %mostrar alfa medio na figura
% text(10, 5750,['hours from~midnight :' num2str(hms)]); %mostrar tempo na figura
% title(sprintf(strcat('Speed Profile_',nome2,'%02d'),i)); %titulo da imagem, vai de 1 ate ao
% ylabel('Height [m]'); %legendas dos eixos
% yticks([0:250:6000]);
% yticklabels({'0','','','','1000','','','','2000','','','','3000','','','','4000','','','','50
% xlabel('Horizontal Wind Speed [m/s]');
% xticks([0:1:30]);
% xticklabels({'0','','','','','5','','','','','10','','','','','15','','','','','20','','','',
%escala do eixo x com tracos de 1 em 1 mas numeros de 5 em 5
% ylim([210 6000]); %limites dos eixos
% xlim([0 30]); %idem
%
% subplot(2,2,[2 4]); %subplot com a direccao
% plot(z,y,'.','Color','k');
% ylabel('Height [m]'); %legendas dos eixos
% yticks([0:250:6000]);
% yticklabels({'0','','','','1000','','','','2000','','','','3000','','','','4000','','','','50
% xlabel('Wind Direction [degree]');
% xticks([0:60:360]);
% ylim([210 6500]); %limites dos eixos
% xlim([0 360]); %idem
%
%
% plot com temperatura
% plot(x,y,'.','Color','r');
% title(sprintf(strcat('Temperature Profile_',nome2,'%02d'),i)); %titulo da imagem, vai de 1 a
% text(0, 1100,['hours/min from approx midnight :' num2str(hms)]); %mostrar tempo na figura
% ylabel('Height [m]'); %legendas dos eixos
% xlabel('RASS Virtual Temperature (corrected for wvert) [degreeC]');
% ylim([10 1200]); %limites dos eixos
% yticks([45:60:1200]);
```

```
% xlim([-5 35]); %idem
% xticks([ -5:1:35]);
% xticklabels({'-5','','','','','0','','','','','5','','','','','10','','','','','15','','',''
%escala do eixo x com tracos de 1 em 1 mas numeros de 5 em 5
%
% set(gcf,'units','centimeters','position',[0,0,20,15]) %definir tamnaho da figura em cm
%
% guardar como os dois formatos
%
%      fig = figure(i);
% filename = sprintf(strcat('SpeedProfile_',nome2,'_%02d.pdf'),i);
%        print( fig, '-dpdf', filename );
%
%
% quando e para fazer 48 imagens isto funciona, se e para fazer so uma e o
% que esta fora do ciclo que funciona
%
%        fig = figure(i);
% filename = sprintf(strcat('SpeedProfile_',nome2,'_%02d.jpg'),i);
%        print( fig, '-djpeg', filename );
%
%       %definir o directorio do sitio onde quero guardar as imagens
%
%        fname = strcat('C:\Users\ZMVilaca\Desktop\tese\ALLFIGURES\profiles\speed_profiles\NCAS
% saveas(gca, fullfile(fname, filename), 'jpeg');
%
% end
```

## .5 Calculate and plot the derivative of wind speed

MATLAB script entitled:

`derivada_velocidade.m`

\lstinputlisting[language=Matlab]{C:/Users/ZMVilaca/Desktop/Tese/Matlab/derivada_velocida

```
%derivada da velocidade

M=perdigaonewa20170501to20170615uvwa60mtwr37sem530; %nome do ficheiro

d=46; %dias a avaliar de 1 a 46, ver comentarios a seguir para resto de
%explicacao
figures=[1:1:d];

nome3='37'

%%----------------Maio------------------

for a=1:1:d-15 %dias de maio a avaliar
dii=a; %dia inicial que se quer estudar de 1 a 45. 1/5/17 e dia 1, 2/5/17
%e dia 2 e sucessivamente ate 15/6/17 dia 44
dff=a; %dia final que se quer estudar de 1 a 45. 1/5/17 e dia 1, 2/5/17
%e dia 2 e sucessivamente ate 15/6/17 dia 44

%o ficheiro tem os dias 4 e 29 repetidos para colmatar o dia 5 e 29, ter
%atencao a isso nas imagens finais

p=(dii-1)*144+1:1:(dff+1)*144-144; %vector que da o intervalo em grupos
%de 10 min que se pretende, de acordo com os dias que se escolheram
p=p'; %transpor esse vector para o transformar em vector coluna

um=M(p,6); %vector so com media de U
vm=M(p,10); %vector so com media de V
vtm=sqrt(um.^2+vm.^2); %norma do vector velocidade media
indicesm = find(abs(vtm)>30); %eliminar valores de velocidade acima de 30m/s
vtm(indicesm) = NaN %idem

difm=diff(vtm)./vtm(1:end-1);
ym=1:1:length(difm);

A{d} = sprintf('May_%d',a); %nomear as figuras de 1 a 31 de maio

fig=figure
    plot(ym,difm);
   title(A{d}); %da o titulo de acordo com os dias
    ylabel('variation');
    xlabel('UTC')
    xlim([0 150]); %limites dos eixos
    xticks([0:12:144]);
    xticklabels([0:2:24]);

      % Output the figure

      filename = sprintf('VariationOfSpeed%02d.jpg',a);
```

```
    print( fig, '-djpeg', filename );

     fname = strcat('C:\Users\ZMVilaca\Desktop\tese\ALLFIGURES\declives\
       ',nome3,'');
saveas(gca, fullfile(fname, filename), 'jpeg');
end

%%----------Junho-----------

for a=d-14:1:d %dias de junho a avaliar
dii=a; %dia inicial que se quer estudar de 1 a 45. 1/5/17 e dia 1, 2/5/17
%e dia 2 e sucessivamente ate 15/6/17 dia 44
dff=a; %dia final que se quer estudar de 1 a 45. 1/5/17 e dia 1, 2/5/17
%e dia 2 e sucessivamente ate 15/6/17 dia 44

%o ficheiro tem os dias 4 e 29 repetidos para colmatar o dia 5 e 29, ter
%atencao a isso nas imagens finais

p=(dii-1)*144+1:1:(dff+1)*144-144; %vector que da o intervalo em grupos
%de 10 min que se pretende, de acordo com os dias que se escolheram
p=p'; %transpor esse vector para o transformar em vector coluna

uj=M(p,6);   %vector so com media de U
vj=M(p,10);  %vector so com media de V
vtj=sqrt(uj.^2+vj.^2); %norma do vector velocidade media
indicesj = find(abs(vtj)>30); %eliminar valores de velocidade acima de 30m/s
vt(indicesj) = NaN %idem
difj=diff(vtj)./vtj(1:end-1);
yj=1:1:length(difj);

A{d} =  sprintf('June %d',a-31); %nomear as figuras de 1 a 15 de junho

fig=figure
    plot(yj,difj);
   title(A{d}); %da o titulo de acordo com os dias
    ylabel('variation');
    xlabel('UTC')
    xlim([0 150]); %limites dos eixos
    xticks([0:12:144]);
    xticklabels([0:2:24]);

      % Output the figure
    filename = sprintf('VariationOfSpeed%02d.jpg',a);
      print( fig, '-djpeg', filename );

     fname = strcat('C:\Users\ZMVilaca\Desktop\tese\ALLFIGURES\declives\
       ',nome3,'');
saveas(gca, fullfile(fname, filename), 'jpeg');
end


% for f = 1:numel(figures)
%       fig = figures(f);
%
%       % Output the figure
%
%       filename = sprintf('VariationOfSpeed%02d.jpg',f);
%       print( fig, '-djpeg', filename );
```

```
% end
```

## .6 Constant periods

MATLAB script entitled:
`EncontrarPeriodosConstantes.m`

\lstinputlisting[language=Matlab]{C:/Users/ZMVilaca/Desktop/Tese/Matlab/EncontrarPeriodos

```
%encontrar blocos de 10 minutos com variacao de velocidade ou direccao
aproximadamente constante
%ha muita coisa comentada que foram tentativas, deica ficar que tem coisas
%que podem ser uteis para corrigir eventuais erros, ou usar para outros
%codigos


S=perdigaonewa20170501to20170615uvwtwr3760melimiadosdefeitos; %ficheiro
%livre de erros

%%:::::::::preenche com NaNs as linhas eliminadas devido a defeitos::::::::

%%------------torre 37-------------------
%
% S = insertrows(S,NaN(30,17),598); %dia 5
% S = insertrows(S,NaN(92,17),1412); %dia 10 e 11
% S = insertrows(S,NaN(120,17),1523); %dia 11 e 12
% S = insertrows(S,NaN(4,17),1646); %dia 12
% S = insertrows(S,NaN(73,17),3440); %dia 24 e 25
% S = insertrows(S,NaN(64,17),3858); %dia 30

u=S(:,6);  %vector so com media de U
v=S(:,10); %vector so com media de V
vt=sqrt(u.^2+v.^2); %norma do vector velocidade media
indices = find(abs(vt)>30); %eliminar valores de velocidade acima de 30m/s
vt(indices) = NaN %idem
%
%% n=6; %numero de grupos de 10 minutos a considerar. 6 e uma hora
%%
%% y = arrayfun(@(i) mean(vt(i:i+n-1), 'omitnan'),1:n:length(vt)-n+1)';
% media horaria da velocidade
%
j=1:length(vt)-1;

% vdif=1-([vt(j+1)]./[vt(j)]); %calcula diferenca em percentagem entre
%velocidades consecutivas
% vdif=abs(vdif); %passa para tudo positivo
%
% indices2=find(vdif<=0.05); %encontrar valores de diferenc entre medias
%de 10 min inferiores a 5 ou 10%
%
% index1=indices2;     % da o indice consecutivo e o seguinte,
% index2=indices2+1;   %caso contrario so mostra um dos dois valores do par
%
%%ciclo para juntar apenas os pares que obedecem a condicao vdif<=0.05/0.10
%
%  nn=1;
%  mm=1;
% indexx = insertrows(index1,index2,repmat(nn:nn:size(index1,1),mm,1));
%%junta os dois vectores
```

```
%
% AA=unique(indexx); %devolve indices2 sem valores repetidos
%
% vvtt=[S(AA,2:5) vt(AA) vdif(AA)];
%
%
% LL=vdif(indices2+1);

%ciclo para juntar apenas os pares que obedecem a condicao vdif<=0.05/0.10

if vdif(indices2+1)<=0.05;
  n=1;
  m=1;
index = insertrows(index1,index2,repmat(n:n:size(index1,1),m,1));
%junta os dois vectores


else
    index=indices2;

end

A=unique(index); %devolve indices2 sem valores repetidos
%
A=A';

%encontrar certo numero de indices seguidos
q=A;
a=diff(q);
b=find([a inf]>1);
c=diff([0 b]); %length of the sequences
f=cumsum(c); %indice de A do fim da sequencia
i=f-c+1; %indice de A do inicio da sequencia

Kf=A(f);  %A com os indices do fim da sequencia
Ki=A(i);  %A com os indices do inicio da sequencia
Af=Kf+1-Ki; %diferenca entre inicio e fim, para obter a largura do
%intervalo (numero de 10 min seguidos)
AFprov=[Ki  %matriz com indice de inicio
    Kf+1      % indice de fim
    Af]';   % numero de 10 minutos decorridos

indx=find(AFprov(:,3)>=6);  %encontrar apenas os intervalos com + de
%6*10 minutos

AF=AFprov(indx,:);  %nova matriz so com esses valores

P1=S(AF(:,1),2:5); %velocidade e tempo correspondente ao primeiro indice
%do intervalo
P2=S(AF(:,2),2:5);  %velocidade e tempo correspondente ao ultimo indice
%do intervalo

Periodos=[AF P1 P2];  %matriz final com indices de inicio, fim, largura
%do intervalo, tempo e velocidade

% vdif1=[vdif
%      NaN];
% O=S(A',2:5);
```

```
% vvtt=[vt(A') vdif1(A') O];
%
%
% A=A';
%
P=S(A,1:5); %devolve a matriz original so com os os periodos desejados
PV=vt(A,:); %descobre valores de velocidade para os indices que cumprem
%o criterio

 Periodos3=[P PV vdif(A)]; % junta as duas matrizes anteriores


% % IndicesConsecutivos=find(diff(indices)==1);
%
% pp=find(diff(A)==1); %encontra indices consecutivos
%
% q1=pp;  % da o indice consecutivo e o seguinte,
% q2=pp+1; %caso contrario so mostra um dos dois valores do par
%
%    n=1;
%    m=1;
% q = insertrows(q1,q2,repmat(n:n:size(q1,1),m,1));  %junta os dois vectores
%
% B=unique(q); %devolve q sem valores repetidos


% x = find(diff(Periodos(:,4))==0); %encontra horas seguidas
%
% q1=x;  % da o indice consecutivo e o seguinte,
% q2=x+1; %caso contrario so mostra um dos dois valores do par
%
%    n=1;
%    m=1;
% q = insertrows(q1,q2,repmat(n:n:size(q1,1),m,1));  %junta os dois vectores
%
% B=unique(q); %devolve q sem valores repetidos
%
%
% PeriodosConsecutivos=[Periodos(B,1:6)];  %matriz com o resultado final,
%indica os periodos e a velocidade
%
```

## .7 Finding constant periods with moving averages

MATLAB script entitled:

PeriodosConstantesMediaMovel.m

\lstinputlisting[language=Matlab]{C:/Users/ZMVilaca/Desktop/Tese/Matlab/PeriodosConstante

```
%periodos constantes media movel

S=perdigaonewa20170501to20170615trw3760mdirecaoeliminadosdefeitos;
%ficheiro livre de erros

%%:::::::::preenche com NaNs as linhas eliminadas devido a defeitos::::::::

%%---------torre 37-----------------
%
S = insertrows(S,NaN(30,9),598); %dia 5
S = insertrows(S,NaN(92,9),1412); %dia 10 e 11
S = insertrows(S,NaN(120,9),1523); %dia 11 e 12
S = insertrows(S,NaN(4,9),1646); %dia 12
S = insertrows(S,NaN(73,9),3440); %dia 24 e 25
S = insertrows(S,NaN(64,9),3858); %dia 30

% u=S(:,6); %vector so com media de U
% v=S(:,10); %vector so com media de V
% vt=sqrt(u.^2+v.^2); %norma do vector velocidade media
% indices = find(abs(vt)>30); %eliminar valores de velocidade acima de 30m/s
% vt(indices) = NaN %idem

vt=S(:,6);
% indices = find(abs(vt)>55); %eliminar valores de velocidade acima de 30m/s
% vt(indices) = NaN %idem


vmm=movmean(vt,3);

j=1:length(vmm)-1;

vdif=1-([vmm(j+1)]./[vmm(j)]); %calcula diferenca em percentagem entre
%velocidades consecutivas
vdif=abs(vdif); %passa para tudo positivo

indices2=find(vdif<=0.02); %encontrar valores de diferenc entre medias de
%10 min inferiores a 5 ou 10%

index1=indices2; % da o indice consecutivo e o seguinte,
index2=indices2+1; %caso contrario so mostra um dos dois valores do par
index2=index2(1:end-1); %eliminar a ultima linha de 6624, senao da asneira
%pq a seguir passa para 6625
%ciclo para juntar apenas os pares que obedecem a condicao vdif<=0.05/0.10


if vdif(index2)<=0.02;
  n=1;
  m=1;
```

```
index = insertrows(index1,index2,repmat(n:n:size(index1,1),m,1));
%junta os dois vectores


 else
     index=indices2;

end

A=unique(index); %devolve indices2 sem valores repetidos
%
A=A';

%encontrar certo numero de indices seguidos
q=A;
a=diff(q);
b=find([a inf]>1);
c=diff([0 b]); %length of the sequences
f=cumsum(c); %indice de A do fim da sequencia
i=f-c+1; %indice de A do inicio da sequencia

Kf=A(f);  %A com os indices do fim da sequencia
Ki=A(i);  %A com os indices do inicio da sequencia
Af=Kf+1-Ki; %diferenca entre inicio e fim, para obter a largura do
%intervalo (numero de 10 min seguidos)
AFprov=[Ki  %matriz com indice de inicio
    Kf+1      % indice de fim
    Af]';   % numero de 10 minutos decorridos

indx=find(AFprov(:,3)>=6);  %encontrar apenas os intervalos com + de
%6*10 minutos

AF=AFprov(indx,:);  %nova matriz so com esses valores

P1=S(AF(:,1),2:5); %velocidade e tempo correspondente ao primeiro indice
%do intervalo
P2=S(AF(:,2),2:5);  %velocidade e tempo correspondente ao ultimo indice
%do intervalo

Periodos=[AF P1 P2];  %matriz final com indices de inicio, fim, largura do
%intervalo, tempo e velocidade

%criar histograma e guarda-lo
hold on
histogram(Periodos(:,3),20);
ylabel('Number of periods','FontSize',17);
xlabel('Number of 10 minute averages', 'FontSize',17);
xlim([5.5 max(Periodos(:,3))+3]) %definir o limite de x como o valor
%maximo de grupos de 10 minutos+3 para ficar com algum espaco a esquerda
% xticks([0:1:length(Periodos(:,3))]); %definir ticks ate o tamanho de
%Periodos
% xticklabels({'0','','','','','5','6','','','','10','','','','','15','',
%'','','','20','','','','','25','','','','','30','','','','','35','','',''
%,'','40','','','','','45','','','','','50','','','','','55','','','','',
%'60'}); %escala do eixo x com tracos de 1 em 1 mas numeros de 5 em 5
xxt = get(gca, 'XTick');
set(gca, 'FontSize', 13);
yticks([0:1:length(Periodos(:,3))]);
```

```
yticklabels({'0','','','','','5','','','','','10','','','','','15','','',
    '','','20','','','','','25','','','','','30','','','','','35','','',
    '','','40','','','','','45','','','','','50','','','','','55','','',
    '','','60'});
    %escala do eixo x com tracos de 1 em 1 mas numeros de 5 em 5
yyt = get(gca, 'YTick');
set(gca, 'FontSize', 13);

title('3 point window moving average histogram of 2% variation');
%titulo da imagem, vai de 1 ate ao numero final ditado por i
hold off
  fig = figure(1);
filename = 'MovMeanDirJanela3Histogram2percent.jpg';
      print( fig, '-djpeg', filename );

   fname = 'C:\Users\ZMVilaca\Desktop\tese\ALLFIGURES\histogramas\';
 saveas(gca, fullfile(fname, filename), 'jpeg');
```

# Weather types and IOP characterization

Santos et al. (2016) Santos et al. (2016) applying a k-means clustering on daily mean sea level pressure within a Western European sector (30° W-10° E, 25-70° N) identified eight regimes for the synoptic weather in Portugal (WT), classified under three main groups, shown in Figure .1:

- S1, S2, S3 (summertime types);
- W1, W2, W3 (wintertime types); and
- B1 and B2 (blocking types).

The frequency of each weather type over the 45 days of the IOP are shown in figure .2.

### Summertime types

S1 pattern reveals a northeastward extended Azores high. The mean frequency of this WT is 20-25% over the 1 May - 15 June period, however, during the IOP this regime was absent (Figure .2). The S2 is characterized by a low over northwestern Europe and an Azores high close to its climatological location. The frequency of this WT during IOP was 13%, below its climatological value. S3 reveals the presence of an Icelandic low and an Azores anticyclone weaker and located south of its position in the other typical summer regimes. S3 was the most frequent WT during the IOP, with a frequency of 43%, clearly above its climatological value.

### Blocking-like types

Regarding the blocking-like types, B1 is characterized by a low west of Iberian Peninsula and by two high pressure systems located to the north and to the south. B2 features an anticyclone over the British Isles, associated with ridge over the eastern North Atlantic. B1 was the second most frequent regime during IOP, having a frequency close to climatological value (17%).

### Wintertime types

With respect to the WT more frequent in winter, W1 is characterized by low pressure systems just westwards of the British Isles, though spreading their influence throughout western Europe. In W2, the Azores high is relatively weak, while the Icelandic low is southerly displaced relatively to its climatological position. Conversely, W3 hints at a strong northeastward displaced Azores high, extending over Southwestern and Central Europe. From the typical winter regimes, W3 was the most frequent during IOP.

We do not know (yet) the correspondence between each of these 8 synoptic categories and the atmospheric conditions at the microscale level, namely the wind speed and direction along the ridges and in the valley. Information about the local conditions is also needed.

Qualitative information was also added, related to cloud level and thunderstorm occurrences.

- Clear sky
- Clear sky (high clouds until 02UTC, 12-15UTC)
- Clear sky (low clouds in afternoon)
- Fog near sunrise (high clouds in evening)
- High and low clouds
- High clouds
- High clouds (evening)
- High clouds (afternoon)
- High clouds (low clouds in evening)
- Low and high clouds
- Low and middle clouds
- Low clouds
- Low clouds (fog near sunrise)
- Low clouds (morning)
- Low clouds (until noon)
- Middle clouds (afternoon)
- Middle clouds (until 17UTC)

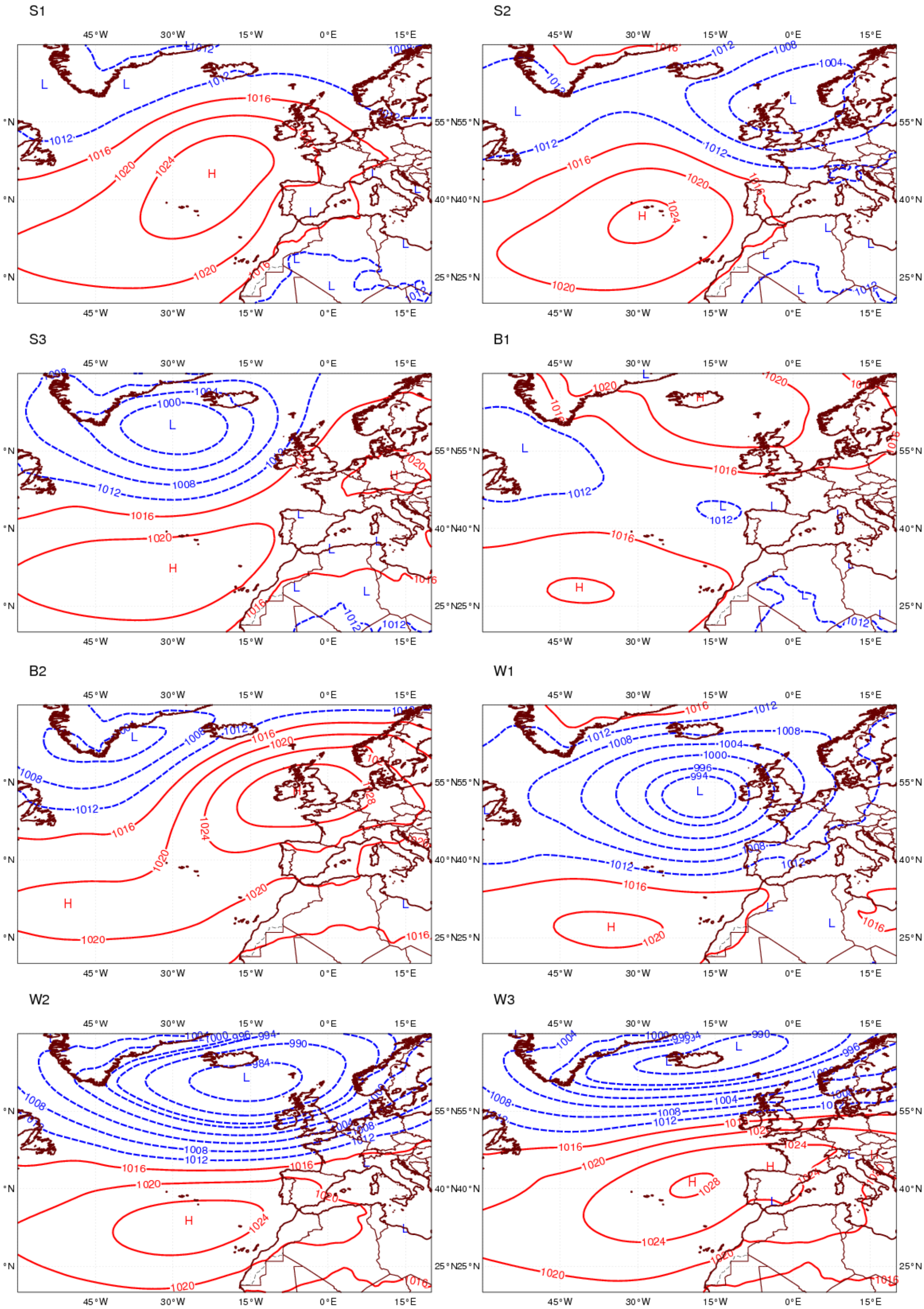



Figure .1: Weather types (left to right and top to bottom: S1, S2, S3, B1, B2, W1, W2 and W3)

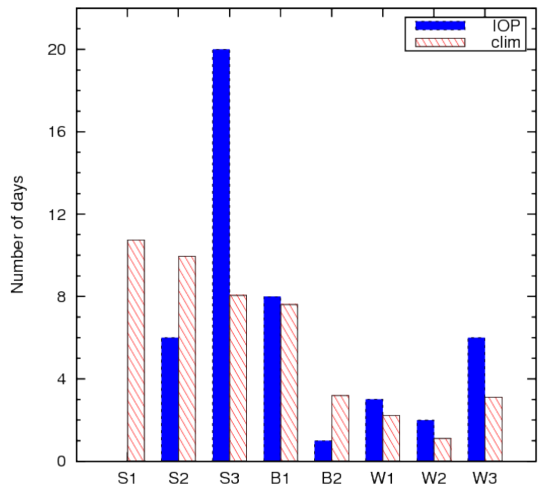



Figure .2: Frequency of 8 weather types during the IOP

- Short mist near sunrise
- Thunderstorm (afternoon)
- Thunderstorm (evening)
- Thunderstorm (late afternoon)
- Thunderstorm (until 02UTC) and fog near sunrise
- Thunderstorm (until 07UTC)

### Precipitation and cloudiness

Precipitation data was based on CLAMPS and precipitation data from Proenca-a-Nova station

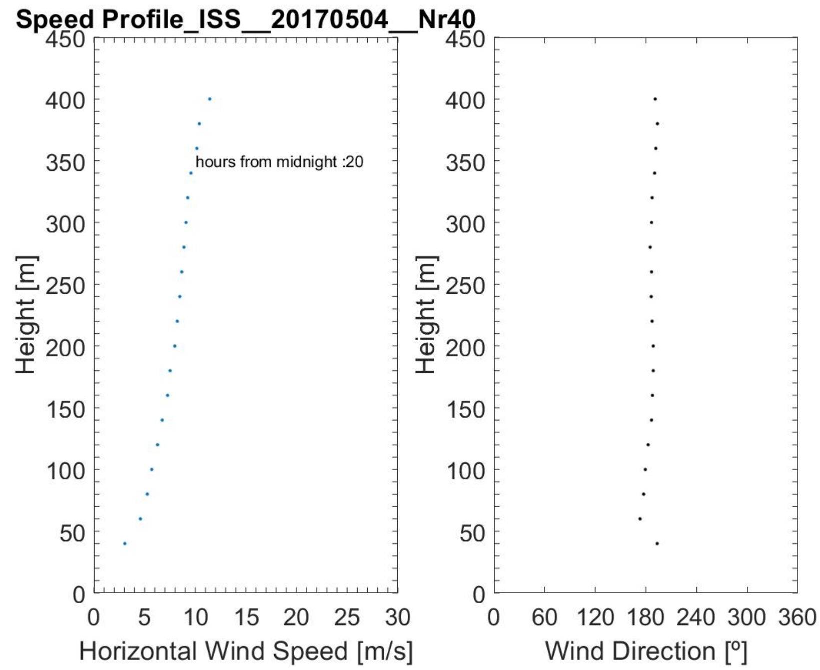
The classification of low, middle and high clouds follows the WMO classification `https://cloudatlas.wmo.int/clouds-definitions.html` using the ceilometer data.

The criterion for fog detection are:

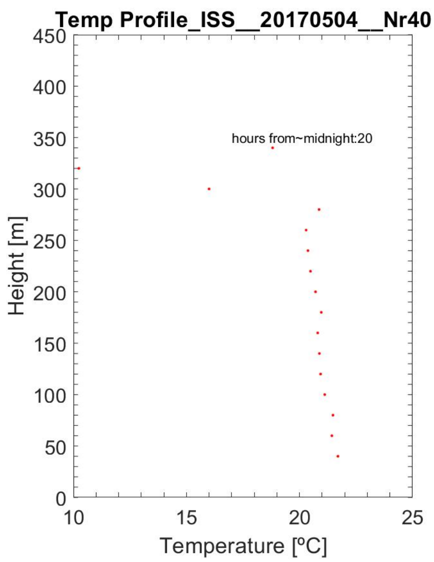
1. Cloud base height is below 200 m;
2. Saturation near the surface (based on sounding data);
3. No precipitation

The criterion for a thunderstorm occurrence is higher than 2 degree lightning (in one hour) within a radius of 25 km of Orange site.

# Remote sensors (wind speed, direction and temperature) May 4 2017




(a) Wind speed and direction




(b) Temperature

Figure .3: May 4; 20:00 UTC at station 123, Sodar-RASS (NCAR)

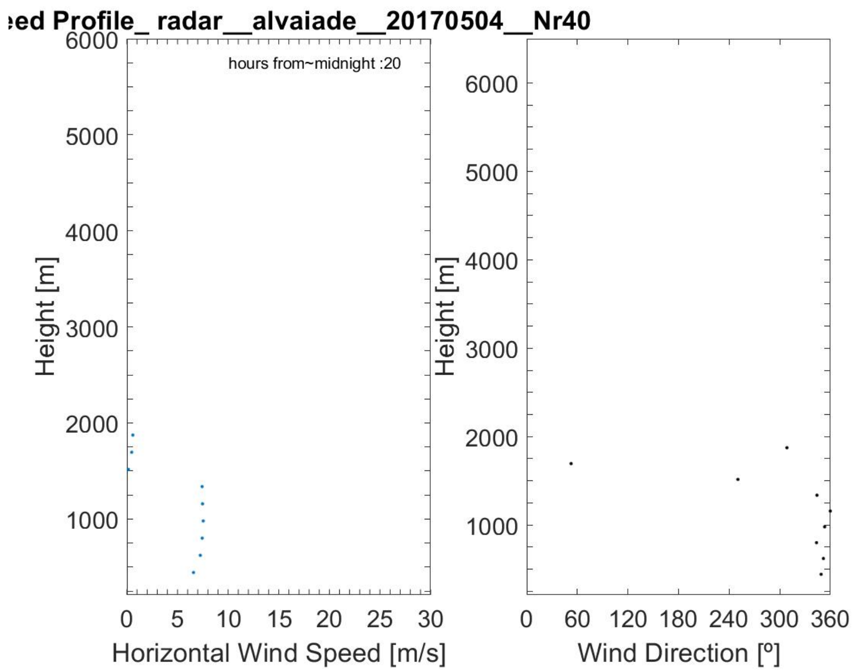
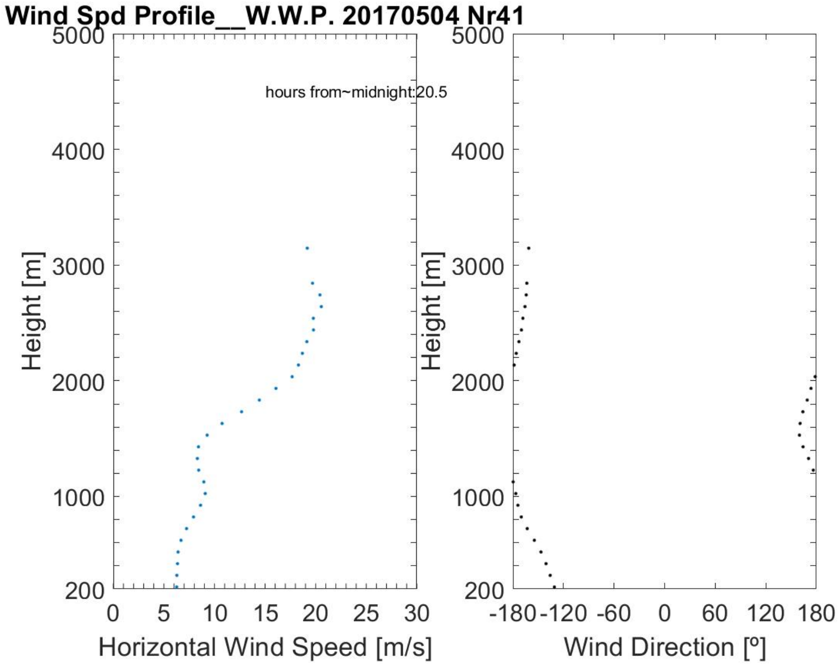
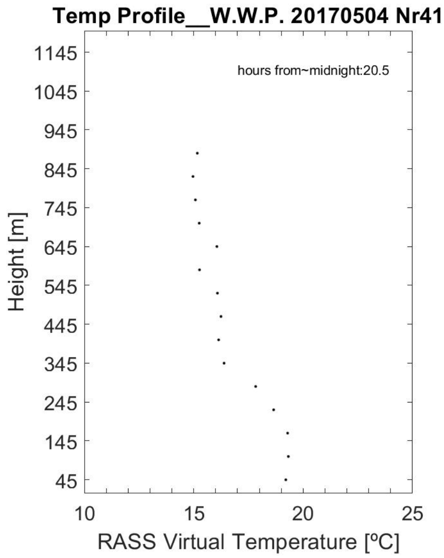



Figure .4: Wind speed and direction profiles (May 4; 20:00 UTC) at station 122, radar wind profiler (NCAR/NCAS)

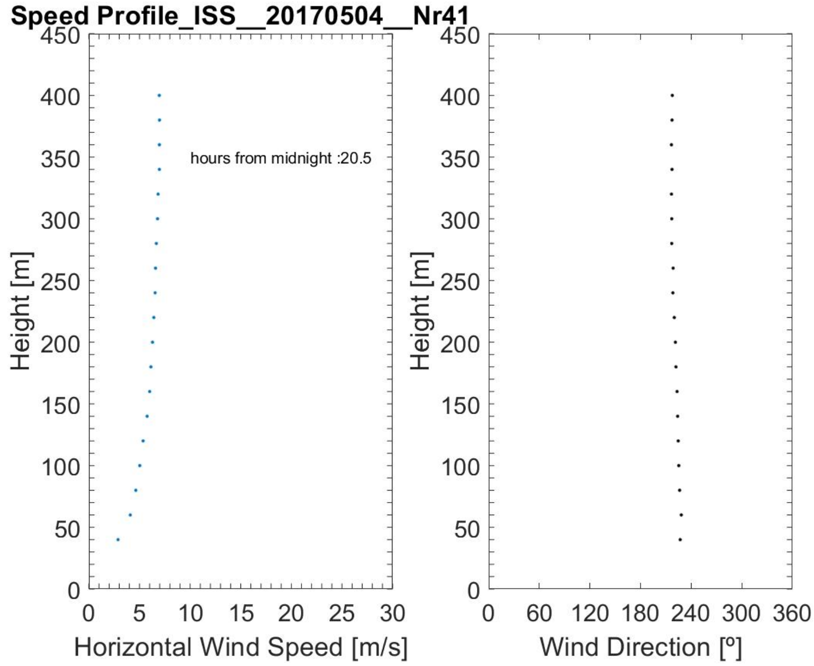



(a) Wind speed and direction

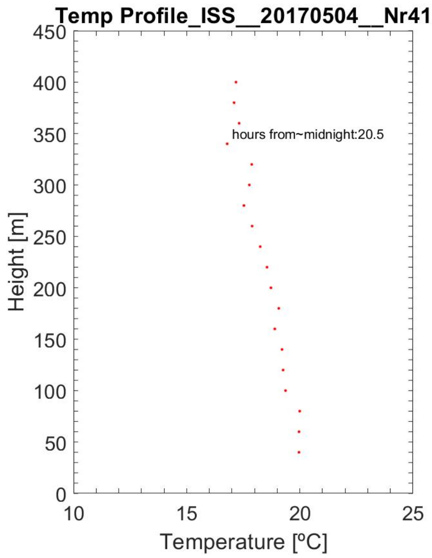



(b) Temperature

Figure .5: May 4; 20:30 UTC at station 121, radar wind profiler & RASS (NCAR)




(a) Wind speed and direction




(b) Temperature

Figure .6: May 4; 23:00 UTC at station 123, Sodar-RASS (NCAR)

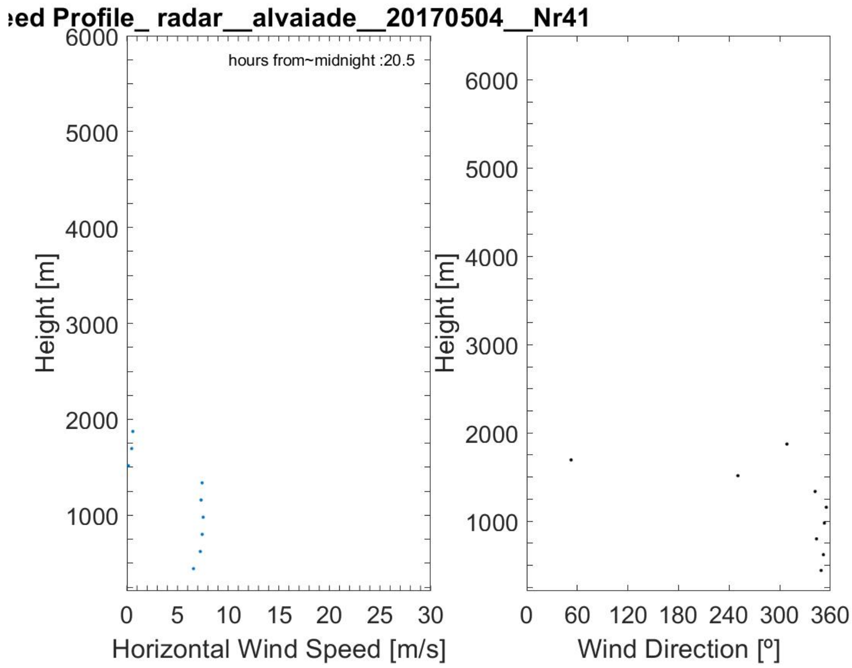
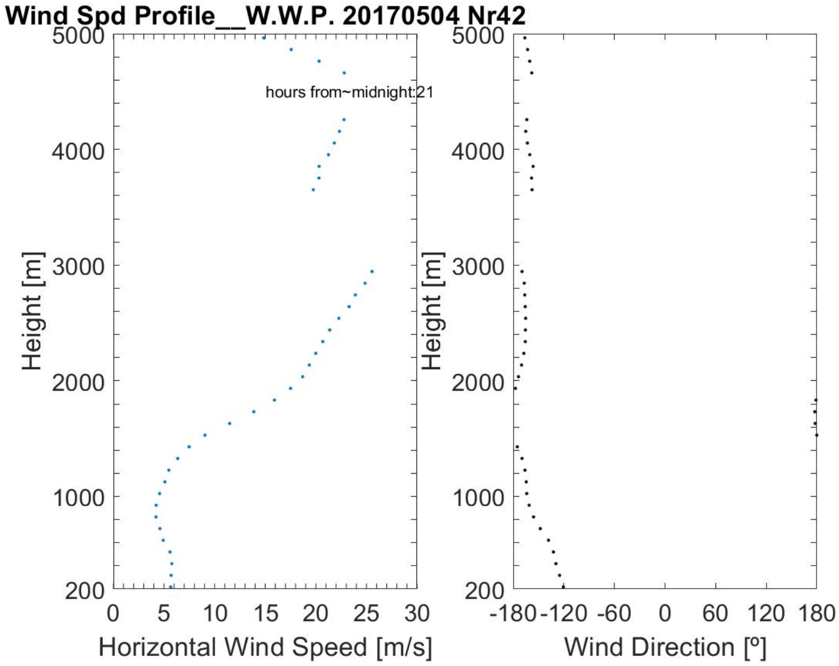
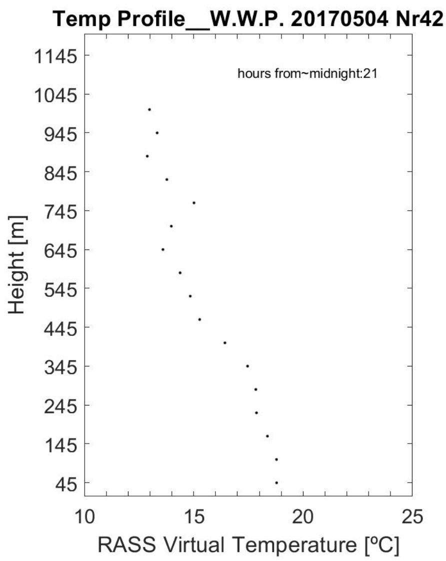



Figure .7: May 4; 20:30 UTC at station 122, radar wind profiler (NCAR/NCAS)

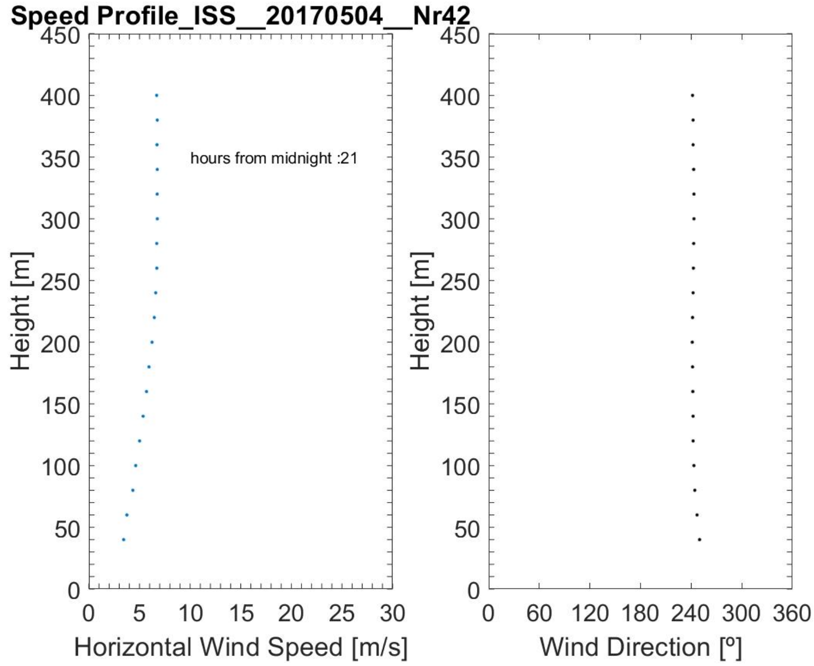



(a) Wind speed and direction

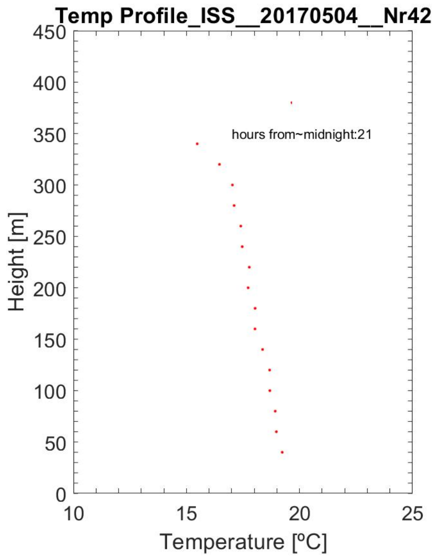



(b) Temperature

Figure .8: May 4; 21:00 UTC at station 121, radar wind profiler & RASS (NCAR)




(a) Wind speed and direction




(b) Temperature

Figure .9: May 4; 21:00 UTC at station 123, Sodar-RASS (NCAR)

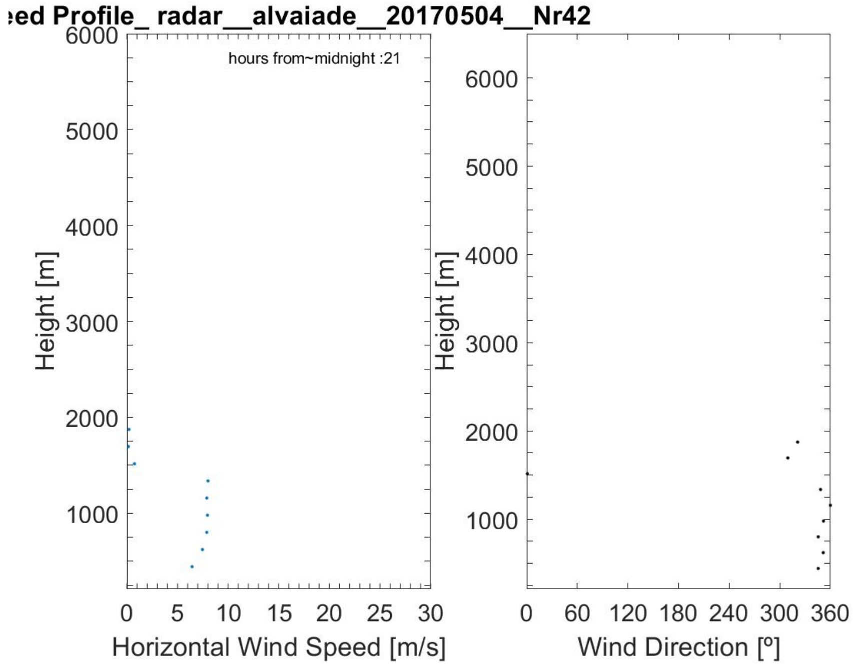
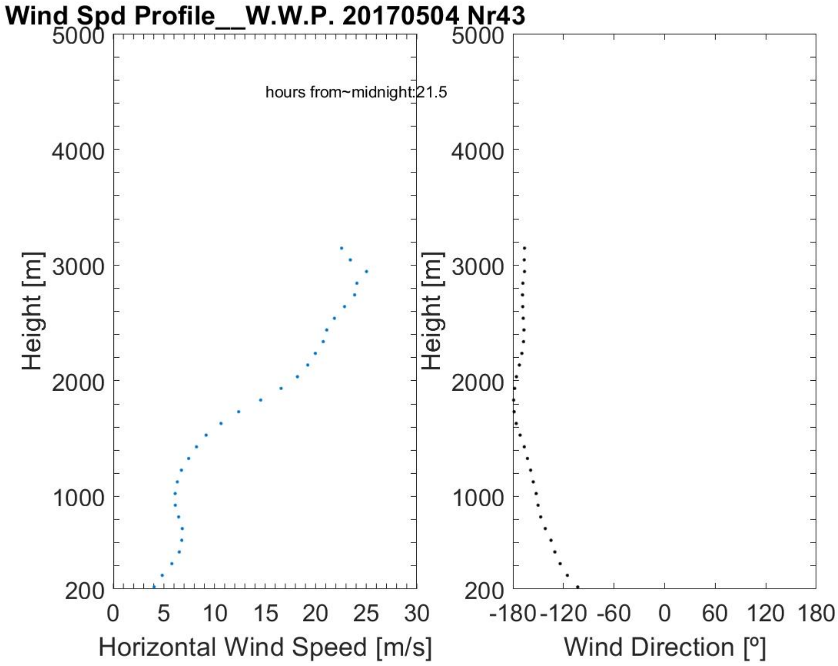
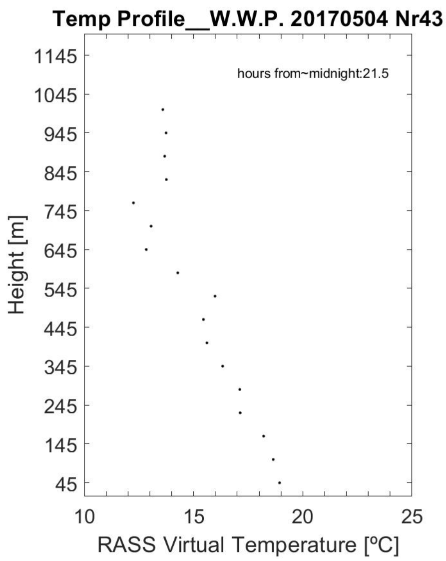



Figure .10: May 4; 21:00 UTC at station 122, radar wind profiler (NCAR/NCAS)

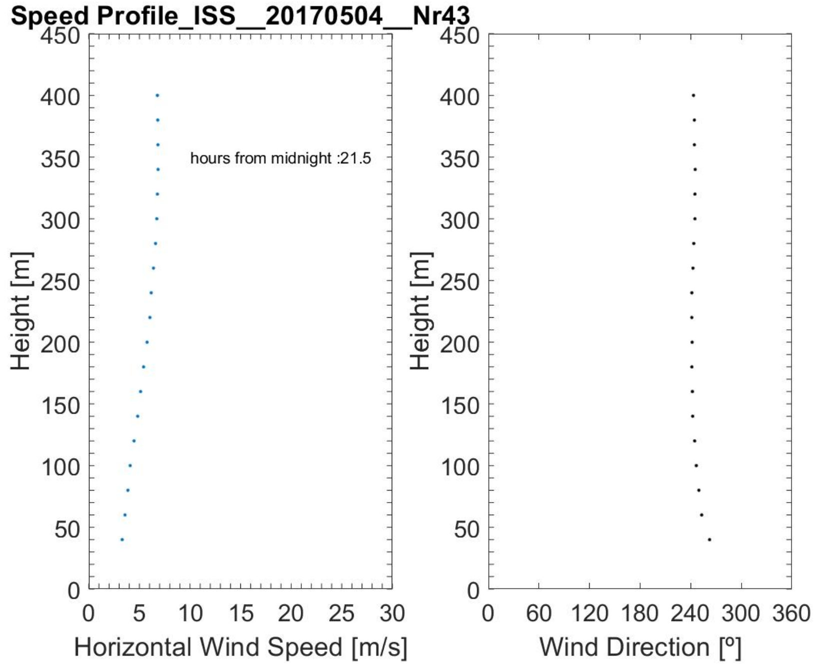



(a) Wind speed and direction

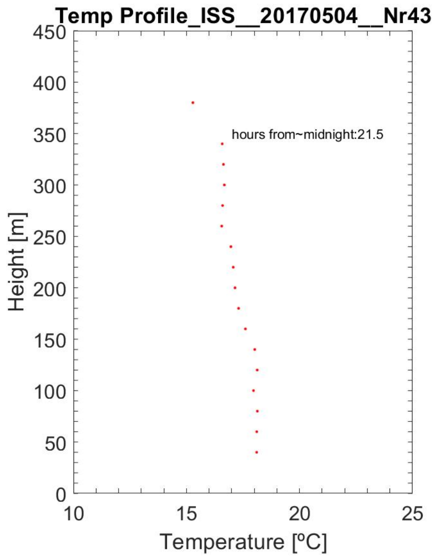



(b) Temperature

Figure .11: May 4; 21:30 UTC at station 121, radar wind profiler & RASS (NCAR)




(a) Wind speed and direction




(b) Temperature

Figure .12: May 4; 21:30 UTC at station 123, Sodar-RASS (NCAR)

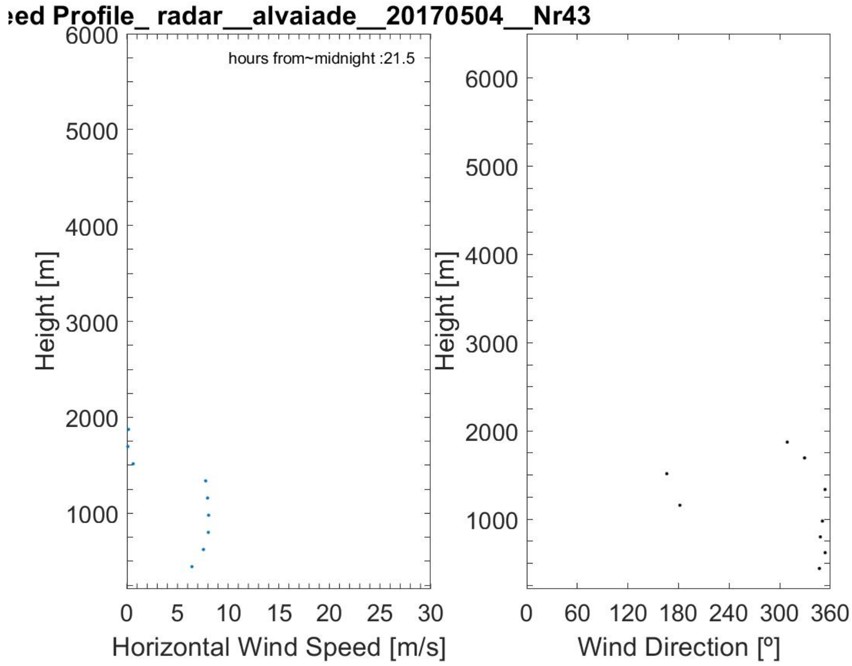



Figure .13: Wind speed and direction profiles (May 4; 21:30 UTC) at station 122, radar wind profiler (NCAR/NCAS)